Elmer G. Ball

ELEMENTS

OF

GEOMETRY.

BY

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PREFACE.

Most persons do not possess, and do not easily acquire, the power of abstraction requisite for apprehending the Geometrical conceptions, and for keeping in mind the successive steps of a continuous argument. Hence, with a very large proportion of beginners in Geometry, it depends mainly upon the *form* in which the subject is presented whether they pursue the study with indifference, not to say aversion, or with increasing interest and pleasure.

In compiling the present treatise, this fact has been kept constantly in view. All unnecessary discussions and scholia have been avoided; and such methods have been adopted as experience and attentive observation, combined with repeated trials, have shown to be most readily comprehended. No attempt has been made to render more intelligible the simple notions of position, magnitude, and direction, which every child derives from observation; but it is believed that these notions have been limited and defined with mathematical precision.

A few symbols, which stand for words and not for operations, have been used, but these are of so great utility in giving *style* and *perspicuity* to the demonstrations that no apology seems necessary for their introduction.

Great pains have been taken to make the page attractive. The figures are large and distinct, and are placed in the middle of the page, so that they fall directly under the eye in immediate connection with the corresponding text. The *given* lines

of the figures are full lines, the lines employed as *aids* in the demonstrations are short-dotted, and the *resulting* lines are long-dotted.

In each proposition a concise statement of what is given is printed in one kind of type, of what is required in another, and the demonstration in still another. The reason for each step is indicated in small type between that step and the one following, thus preventing the necessity of interrupting the process of the argument by referring to a previous section. The number of the section, however, on which the reason depends is placed at the side of the page. The constituent parts of the propositions are carefully marked. *Moreover, each distinct assertion in the demonstrations, and each particular direction in the constructions of the figures, begins a new line; and in no case is it necessary to turn the page in reading a demonstration.*

This arrangement presents obvious advantages. The pupil perceives at once what is given and what is required, readily refers to the figure at every step, becomes perfectly familiar with the language of Geometry, acquires facility in simple and accurate expression, rapidly *learns to reason*, and lays a foundation for the complete establishing of the science.

A few propositions have been given that might properly be considered as corollaries. The reason for this is the great difficulty of convincing the average student that any importance should be attached to a corollary. Original exercises, however, have been given, not too numerous or too difficult to discourage the beginner, but well adapted to afford an effectual test of the degree in which he is *mastering* the subjects of his reading. Some of these exercises have been placed in the early part of the work in order that the student may discover, at the outset, that to commit to memory a number of theorems and to reproduce them in an examination is a useless and pernicious labor; but to learn their uses and applications, and to acquire a readiness in exemplifying their utility, is to derive the full benefit of that mathematical training which looks not so much to the

attainment of information as to the *discipline of the mental faculties.*

It only remains to express my sense of obligation to DR. D. F. WELLS for valuable assistance, and to the University Press for the elegance with which the book has been printed; and also to give assurance that any suggestions relating to the work will be thankfully received.

G. A. WENTWORTH.

PHILLIPS EXETER ACADEMY,
January, 1878.

NOTE TO THIRD EDITION.

In this edition I have endeavored to present a more rigorous, but not less simple, treatment of Parallels, Ratio, and Limits. The changes are not sufficient to prevent the simultaneous use of the old and new editions in the class; still they are very important, and have been made after the most careful and prolonged consideration.

I have to express my thanks for valuable suggestions received from many correspondents; and a special acknowledgment is due from me to Professor C. H. JUDSON, of Furman University, Greenville, South Carolina, to whom I am indebted for assistance in effecting many improvements in this edition.

TO THE TEACHER.

When the pupil is reading each Book for the first time, it will be well to let him write his proofs on the blackboard in his own language; care being taken that his language be the simplest possible, that the arrangement of work be vertical (without side work), and that the figures be accurately constructed.

This method will furnish a valuable exercise as a language lesson, will cultivate the habit of neat and orderly arrangement of work, and will allow a brief interval for deliberating on each step.

After a Book has been read in this way the pupil should review the Book, and should be required to draw the figures free-hand. He

should state and prove the propositions orally, using a pointer to indicate on the figure every line and angle named. He should be encouraged, in reviewing each Book, to do the original exercises; to state the converse of propositions; to determine from the statement, if possible, whether the converse be true or false, and if the converse be true to demonstrate it; and also to give well-considered answers to questions which may be asked him on many propositions.

The Teacher is strongly advised to illustrate, geometrically and arithmetically, the principles of limits. Thus a rectangle with a constant base b, and a variable altitude x, will afford an obvious illustration of the axiomatic truth contained in [4], page 88. If x increase and approach the altitude a as a limit, the area of the rectangle increases and approaches the area of the rectangle $a\,b$ as a limit; if, however, x decrease and approach zero as a limit, the area of the rectangle decreases and approaches zero for a limit. An arithmetical illustration of this truth would be given by multiplying a constant into the approximate values of any repetend. If, for example, we take the constant 60 and the repetend .3333, etc., the approximate values of the repetend will be $\frac{3}{10}$, $\frac{33}{100}$, $\frac{333}{1000}$, $\frac{3333}{10000}$, etc., and these values multiplied by 60 give the series 18, 19.8, 19.98, 19.998, etc., which evidently approach 20 as a limit; but the product of 60 into $\frac{1}{3}$ (the limit of the repetend .333, etc.) is also 20.

Again, if we multiply 60 into the different values of the decreasing series, $\frac{1}{30}$, $\frac{1}{300}$, $\frac{1}{3000}$, $\frac{1}{30000}$, etc., which approaches zero as a limit, we shall get the decreasing series, 2, $\frac{1}{5}$, $\frac{1}{50}$, $\frac{1}{500}$, etc.; and this series evidently approaches zero as a limit.

In this way the pupil may easily be led to a complete comprehension of the whole subject of limits.

The Teacher is likewise advised to give frequent written examinations. These should not be too difficult, and sufficient time should be allowed for accurately constructing the figures, for choosing the best language, and for determining the best arrangement.

The time necessary for the reading of examination-books will be diminished by more than one-half, if the use of the symbols employed in this book be permitted.

G. A. W.

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January, 1879.

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PLANE GEOMETRY.

ELEMENTS OF GEOMETRY.

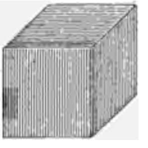
BOOK I.

RECTILINEAR FIGURES.

Introductory Remarks.

A rough block of marble, under the stone-cutter's hammer, may be made to assume *regularity of form.*

If a block be cut in the shape represented in this diagram,



It will have *six flat faces.*

Each *face* of the block is called a *Surface.*

If these surfaces be made smooth by polishing, so that, when a straight-edge is applied to any one of them, the straight-edge in every part will touch the surface, the surfaces are called *Plane Surfaces.*

The sharp edge in which any two of these surfaces meet is called a *Line.*

The place at which any three of these lines meet is called a *Point.*

If now the block be removed, we may think of the *place* occupied by the block as being of precisely the same shape and size as the block itself; also, as having *surfaces* or *boundaries* which separate it from surrounding space. We may likewise think of these surfaces as having *lines* for their boundaries or limits; and of these lines as having *points* for their extremities or limits.

A *Solid,* as the term is used in Geometry, is a limited portion of space.

After we acquire a clear notion of surfaces as boundaries of solids, we can easily conceive of surfaces apart from solids, and

suppose them of *unlimited extent.* Likewise we can conceive of lines apart from surfaces, and suppose them of *unlimited length;* of points apart from lines as having *position,* but *no extent.*

DEFINITIONS.

1. DEF. *Space* or *Extension* has three *Dimensions,* called *Length, Breadth,* and *Thickness.*

2. DEF. A *Point* has position without extension.

3. DEF. A *Line* has only *one* of the dimensions of extension, namely, *length.*

The lines which we draw are only imperfect representations of the true lines of Geometry.

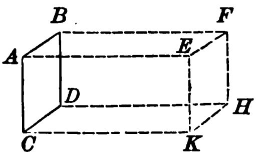
A line may be conceived as traced or generated by a point in motion.

4. DEF. A *Surface* has only *two* of the dimensions of extension, *length* and *breadth.*

A surface may be conceived as generated by a line in motion.

5. DEF. A *Solid* has the *three* dimensions of extension, *length, breadth,* and *thickness.* Hence a solid extends in all directions.

A solid may be conceived as generated by a surface in motion.



Thus, in the diagram, let the upright surface $A\,B\,C\,D$ move to the right to the position $E\,F\,H\,K$. The points A, B, C, and D will generate the lines $A\,E$, $B\,F$, $C\,K$, and $D\,H$ respectively. And the lines $A\,B$, $B\,D$, $D\,C$, and $A\,C$ will generate the surfaces $A\,F$, $B\,H$, $D\,K$, and $A\,K$ respectively. And the surface $A\,B\,C\,D$ will generate the solid $A\,H$.

The relative situation of the two points A and H involves *three, and only three, independent elements.* To pass from A to H it is necessary to move East (if we suppose the direction $A\,E$ to

be due East) a distance equal to $A\,E$, North a distance equal to $E\,F$, and down a distance equal to $F\,H$.

These three dimensions we designate for convenience length, breadth, and thickness.

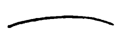
6. The limits (extremities) of lines are points.
The limits (boundaries) of surfaces are lines.
The limits (boundaries) of solids are surfaces.

7. Def. Extension is also called *Magnitude*.

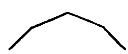
When reference is had to *extent*, lines, surfaces, and solids are called *magnitudes*.

8. Def. A *Straight* line is a line which has the same direction throughout its whole extent.

9. Def. A *Curved* line is a line which changes its direction at every point.



10. Def. A *Broken* line is a series of connected straight lines.



When the word line is used a straight line is meant; and when the word curve is used a curved line is meant.

11. Def. A *Plane Surface*, or a *Plane*, is a surface in which, if any two points be taken, the straight line joining these points will lie wholly in the surface.

12. Def. A *Curved Surface* is a surface no part of which is plane.

13. *Figure* or *form* depends upon the relative position of points. Thus, the figure or form of a line (straight or curved) depends upon the relative position of points in that line; the figure or form of a surface depends upon the relative position of points in that surface.

When reference is had to *form* or *shape*, lines, surfaces, and solids are called *figures*.

14. Def. A *Plane Figure* is a figure, all points of which are in the same plane.

15. Def. *Geometry* is the science which treats of *position, magnitude*, and *form.*

Points, lines, surfaces, and solids, with their relations, are the *geometrical conceptions*, and constitute the subject-matter of Geometry.

16. Plane Geometry treats of plane figures.

Plane figures are either rectilinear, curvilinear, or mixtilinear.

Plane figures formed by straight lines are called *rectilinear* figures; those formed by curved lines are called *curvilinear* figures; and those formed by straight and curved lines are called *mixtilinear* figures.

17. Def. Figures which have the same *form* are called *Similar Figures.* Figures which have the same *extent* are called *Equivalent Figures.* Figures which have the same *form and extent* are called *Equal Figures.*

On Straight Lines.

18. If the direction of a straight line and a point in the line be known, the position of the line is known; that is, a straight line is determined in position if its direction and one of its points be known.

Hence, *all straight lines which pass through the same point in the same direction coincide.*

Between two points one, and but one, straight line can be drawn; that is, *a straight line is determined in position if two of its points be known.*

Of all lines between two points, the *shortest* is the straight line; and the straight line is called the *distance* between the two points.

The point *from* which a line is drawn is called its *origin*.

19. If a line, as CB, $\underline{A\quad C\quad B}$, be produced through C, the portions CB and CA may be regarded as different lines having *opposite directions* from the point C.

Hence, every straight line, as AB, $\underline{A\qquad B}$, has two opposite directions, namely from A toward B, which is expressed by saying line AB, and from B toward A, which is expressed by saying line BA.

20. If a straight line change its magnitude, it must become longer or shorter. Thus by prolonging AB to C, $\underline{A\quad B\quad C}$, $AC = AB + BC$; and conversely, $BC = AC - AB$.

If a line increase so that it is prolonged by its own magnitude several times in succession, the line is *multiplied*, and the resulting line is called a *multiple* of the given line. Thus, if $AB = BC = CD$, etc., $\underline{A\quad B\quad C\quad D\quad E}$, then $AC = 2\,AB$, $AD = 3\,AB$, etc.

It must also be possible to divide a given straight line into an assigned number of equal parts. For, assumed that the nth part of a given line were not attainable, then the double, triple, quadruple, of the nth part would not be attainable. Among these multiples, however, we should reach the nth multiple of this nth part, that is, the line itself. Hence, the line itself would not be attainable; which contradicts the hypothesis that we have the given line before us.

Therefore, *it is always possible to add, subtract, multiply, and divide lines of given length.*

21. Since every straight line has the property of direction, it must be true that two straight lines have either the *same direction* or *different directions*.

Two straight lines which have the same direction, without coinciding, can never meet; for if they could meet, then we should have two straight lines passing through the same point in the same direction. Such lines, however, coincide. § 18

22. *Two straight lines which lie in the same plane and have different directions must meet if sufficiently prolonged; and must have one, and but one, point in common.*

Conversely: *Two straight lines lying in the same plane which do not meet have the same direction;* for if they had different directions they would meet, which is contrary to the hypothesis that they do not meet.

Two straight lines which meet have different directions; for if they had the same direction they would never meet (§ 21), which is contrary to the hypothesis that they do meet.

On Plane Angles.

23. Def. An *Angle* is the difference in direction of two lines. The point in which the lines (prolonged if necessary) meet is called the *Vertex,* and the lines are called the *Sides* of the angle.

An angle is designated by placing a letter at its vertex, and one at each of its sides. In reading, we name the three letters, putting the letter at the vertex *between* the other two. When the point is the vertex of but one angle we usually name the letter at the vertex only; thus, in Fig. 1, we read the angle by

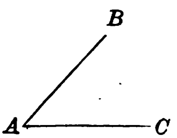


Fig. 1.

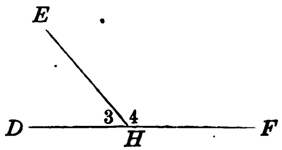
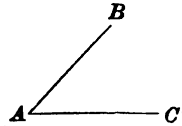


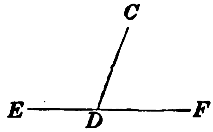
Fig. 2.

calling it angle A. But in Fig. 2, H is the common vertex of two angles, so that if we were to say the angle H, it would not be known whether we meant the angle marked 3 or that marked 4. We avoid all ambiguity by reading the former as the angle EHD, and the latter as the angle EHF.

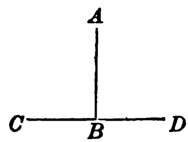
The magnitude of an angle depends wholly upon the *extent of opening* of its sides, and not upon their length. Thus if the sides of the angle $B\,A\,C$, namely, $A\,B$ and $A\,C$, be prolonged, their *extent of opening* will not be altered, and the *size* of the angle, consequently, will not be changed.



24. Def. *Adjacent Angles* are angles having a common vertex and a common side between them. Thus the angles $C\,D\,E$ and $C\,D\,F$ are adjacent angles.

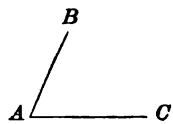


25. Def. A *Right Angle* is an angle included between two straight lines which meet each other so that the two adjacent angles formed by producing one of the lines through the vertex are equal. Thus if the straight line $A\,B$ meet the straight line $C\,D$ so that the adjacent angles $A\,B\,C$ and $A\,B\,D$ are equal to one another, each of these angles is called a right angle.

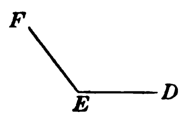


26. Def. *Perpendicular Lines* are lines which make a right angle with each other.

27. Def. An *Acute Angle* is an angle less than a right angle; as the angle $B\,A\,C$.

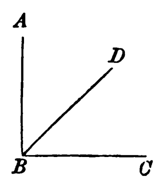


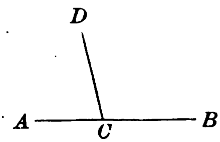
28. Def. An *Obtuse Angle* is an angle greater than a right angle; as the angle $D\,E\,F$.



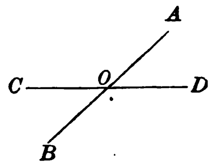
29. Def. Acute and obtuse angles, in distinction from right angles, are called *oblique angles;* and intersecting lines which are not perpendicular to each other are called *oblique lines.*

30. Def. The *Complement* of an angle is the difference between a right angle and the given angle. Thus $A\,B\,D$ is the complement of the angle $D\,B\,C$; also $D\,B\,C$ is the complement of the angle $A\,B\,D$.



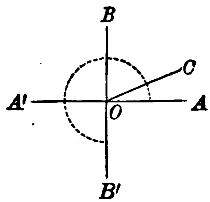


31. Def. The *Supplement* of an angle is the difference between two right angles and the given angle. Thus $A\,C\,D$ is the supplement of the angle $D\,C\,B$; also $D\,C\,B$ is the supplement of the angle $A\,C\,D$.



32. Def. *Vertical Angles* are angles which have the same vertex, and their sides extending in opposite directions. Thus the angles $A\,O\,D$ and $C\,O\,B$ are vertical angles, as also the angles $A\,O\,C$ and $D\,O\,B$.

On Angular Magnitude.



33. Let the lines $B\,B'$ and $A\,A'$ be in the same plane, and let $B\,B'$ be perpendicular to $A\,A'$ at the point O.

Suppose the straight line $O\,C$ to move in this plane from coincidence with $O\,A$, about the point O as a pivot, to the position $O\,C$; then the line $O\,C$ *describes* or *generates* the angle $A\,O\,C$.

The *amount of rotation* of the line, from the position $O\,A$ to the position $O\,C$, is the *Angular Magnitude* $A\,O\,C$.

If the rotating line move from the position $O\,A$ to the position $O\,B$, perpendicular to $O\,A$, it generates a right angle; to the position $O\,A'$ it generates two right angles; to the position $O\,B'$, as indicated by the dotted line, it generates three right angles; and if it continue its rotation to the position $O\,A$, whence it started, it generates four right angles.

Hence the whole angular magnitude about a point in a plane is equal to four right angles, and the angular magnitude about a point on one side of a straight line drawn through that point is equal to two right angles.

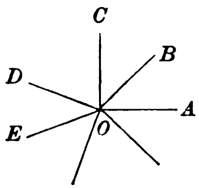


Fig. 1.

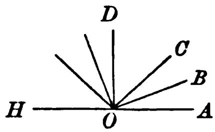
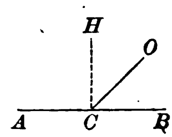


Fig. 2.

34. Now since the angular magnitude about the point O is neither increased nor diminished by the number of lines which radiate from that point, *the sum of all the angles about a point in a plane,* as $AOB + BOC + COD$, etc., in Fig. 1, *is equal to four right angles;* and *the sum of all the angles about a point on one side of a straight line drawn through that point,* as $AOB + BOC + COD$, etc., Fig. 2, *is equal to two right angles.*



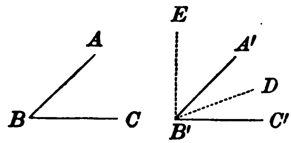
Hence two adjacent angles, OCA and OCB, formed by two straight lines, of which one is produced from the point of meeting in both directions, are *supplements* of each other, and may be called *supplementary adjacent* angles.

On the Method of Superposition.

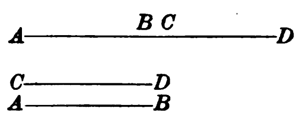
35. The test of the equality of two geometrical magnitudes is that they coincide point for point.

Thus, two straight lines are equal, if they can be so placed that the points at their extremities coincide. Two angles are equal, if they can be so placed that their vertices coincide in position and their sides in direction.

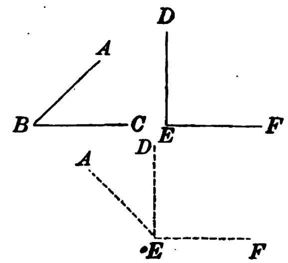
In applying this test of equality, we assume that a line may be moved from one place to another without altering its length; that an angle may be taken up, turned over, and put down, without altering the *difference in direction* of its sides.



This method enables us to compare unequal magnitudes of the same kind. Suppose we have two angles, ABC and $A'B'C'$. Let the side BC be placed on the side $B'C'$, so that the vertex B shall fall on B', then if the side BA fall on $B'A'$, the angle ABC equals the angle $A'B'C'$; if the side BA fall between $B'C'$ and $B'A'$ in the direction $B'D$, the angle ABC is less than $A'B'C'$; but if the side BA fall in the direction $B'E$, the angle ABC is greater than $A'B'C'$.



This method of superposition enables us to add magnitudes of the same kind. Thus, if we have two straight lines AB and CD, by placing the point C on B, and keeping CD in the same direction with AB, we shall have one continuous straight line AD equal to the sum of the lines AB and CD.



Again: if we have the angles ABC and DEF, by placing the vertex B on E and the side BC in the direction of ED, the angle ABC will take the position AED, and the angles DEF and ABC will together equal the angle AEF.

Mathematical Terms.

36. Def. A *Demonstration* is a course of reasoning by which the truth or falsity of a particular statement is logically established.

37. Def. A *Theorem* is a truth to be demonstrated.

38. Def. A *Construction* is a graphical representation of a geometrical conception.

39. Def. A *Problem* is a construction to be effected, or a question to be investigated.

40. Def. An *Axiom* is a truth which is admitted without demonstration.

41. Def. A *Postulate* is a problem which is admitted to be possible.

42. Def. A *Proposition* is either a theorem or a problem.

43. Def. A *Corollary* is a truth easily deduced from the proposition to which it is attached.

44. Def. A *Scholium* is a remark upon some particular feature of a proposition.

45. Def. An *Hypothesis* is a supposition made in the enunciation of a proposition, or in the course of a demonstration.

46. Axioms.

1. Things which are equal to the same thing are equal to each other.
2. When equals are added to equals the sums are equal.
3. When equals are taken from equals the remainders are equal.
4. When equals are added to unequals the sums are unequal.
5. When equals are taken from unequals the remainders are unequal.
6. Things which are double the same thing, or equal things, are equal to each other.
7. Things which are halves of the same thing, or of equal things, are equal to each other.
8. The whole is greater than any of its parts.
9. The whole is equal to all its parts taken together.

47. Postulates.

Let it be granted —

1. That a straight line can be drawn from any one point to any other point.
2. That a straight line can be produced to any distance, or can be terminated at any point.
3. That the circumference of a circle can be described about any centre, at any distance from that centre.

48. Symbols and Abbreviations.

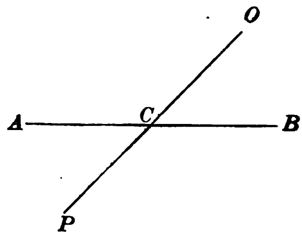
$\therefore$ therefore.
$=$ is (or are) equal to.
$\angle$ angle.
$\angle$s angles.
$\triangle$ triangle.
$\triangle$s triangles.
$\parallel$ parallel.
$\square$ parallelogram
$\square$s parallelograms.
$\perp$ perpendicular.
$\perp$s perpendiculars.
rt. $\angle$ right angle.
rt. $\angle$s right angles.
$>$ is (or are) greater than.
$<$ is (or are) less than.
rt. $\triangle$ right triangle.
rt. $\triangle$s right triangles.
$\odot$ circle.
$\odot$s circles.
$+$ increased by.
$-$ diminished by.
$\times$ multiplied by.
$\div$ divided by.

Post. postulate.
Def. definition.
Ax. axiom.
Hyp. hypothesis.
Cor. corollary.
Q. E. D. quod erat demonstrandum.
Q. E. F. quod erat faciendum.
Adj. adjacent.
Ext.-int. exterior-interior.
Alt.-int. alternate-interior.
Iden. identical.
Cons. construction.
Sup. supplementary.
Sup. adj. supplementary-adjacent.
Ex. exercise.
Ill. illustration.

On Perpendicular and Oblique Lines.

Proposition I. Theorem.

49. *When one straight line crosses another straight line the vertical angles are equal.*



Let line OP cross AB at C.

We are to prove $\angle OCB = \angle ACP$.

$\angle OCA + \angle OCB = 2$ rt. $\angle s$, § 34
(being sup.-adj. $\angle s$).

$\angle OCA + \angle ACP = 2$ rt. $\angle s$, § 34
(being sup.-adj. $\angle s$).

$\therefore \angle OCA + \angle OCB = \angle OCA + \angle ACP$. Ax. 1.

Take away from each of these equals the common $\angle OCA$.

Then $\angle OCB = \angle ACP$.

In like manner we may prove

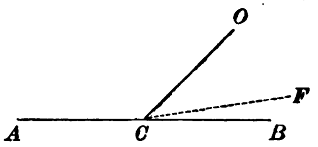
$$\angle ACO = \angle PCB.$$

Q. E. D.

50. Corollary. If two straight lines cut one another, the four angles which they make at the point of intersection are together equal to four right angles.

PROPOSITION II. THEOREM.

51. *When the sum of two adjacent angles is equal to two right angles, their exterior sides form one and the same straight line.*



Let the adjacent angles $\angle\ OCA + \angle\ OCB = $ ***2 rt.*** $\measuredangle$.

We are to prove AC and CB in the same straight line.

Suppose CF to be in the same straight line with AC.

Then $\angle\ OCA + \angle\ OCF = 2$ rt. $\measuredangle$. § 34
(*being sup.-adj.* $\measuredangle$).

But $\angle\ OCA + \angle\ OCB = 2$ rt. $\measuredangle$. Hyp.

$\therefore \angle\ OCA + \angle\ OCF = \angle\ OCA + \angle\ OCB$. Ax. 1.

Take away from each of these equals the common $\angle\ OCA$.

Then $\angle\ OCF = \angle\ OCB$.

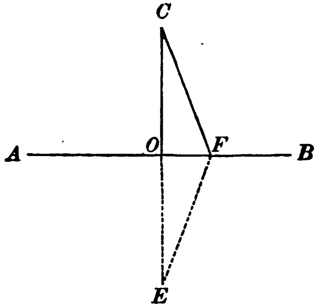
$\therefore$ CB and CF coincide, and cannot form two lines as represented in the figure.

$\therefore$ AC and CB are in the same straight line.

Q. E. D.

Proposition III. Theorem.

52. *A perpendicular measures the shortest distance from a point to a straight line.*



Let $A B$ be the given straight line, C the given point, and $C O$ the perpendicular.

We are to prove $C O <$ *any other line drawn from* C *to* $A B$, *as* $C F$.

Produce $C O$ to E, making $O E = C O$.

Draw $E F$.

On $A B$ as an axis, fold over $O C F$ until it comes into the plane of $O E F$.

The line $O C$ will take the direction of $O E$,

(*since* $\angle C O F = \angle E O F$, *each being a rt.* $\angle$).

The point C will fall upon the point E,

(*since* $O C = O E$ *by cons.*).

$\therefore$ line $C F =$ line $F E$, § 18

(*having their extremities in the same points*).

$\therefore C F + F E = 2 C F$,

and $C O + O E = 2 C O$. Cons.

But $C O + O E < C F + F E$, § 18

(*a straight line is the shortest distance between two points*).

Substitute $2 C O$ for $C O + O E$,

and $2 C F$ for $C F + F E$; then we have

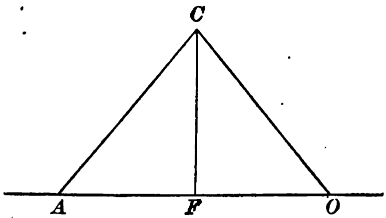
$2 C O < 2 C F$.

$\therefore C O < C F$.

Q. E. D.

PROPOSITION IV. THEOREM.

53. *Two oblique lines drawn from a point in a perpendicular, cutting off equal distances from the foot of the perpendicular, are equal.*



Let FC be the perpendicular, and CA and CO two oblique lines cutting off equal distances from F.

We are to prove $CA = CO$.

Fold over CFA, on CF as an axis, until it comes into the plane of CFO.

FA will take the direction of FO,
(*since* $\angle CFA = \angle CFO$, *each being a rt.* $\angle$).

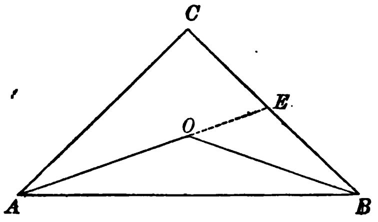
Point A will fall upon point O,
($FA = FO$, *by hyp.*).

$\therefore$ line CA = line CO, § 18
(*their extremities being the same points*).

Q. E. D.

PROPOSITION V. THEOREM.

54. *The sum of two lines drawn from a point to the extremities of a straight line is greater than the sum of two other lines similarly drawn, but included by them.*



Let CA and CB be two lines drawn from the point C to the extremities of the straight line AB. Let OA and OB be two lines similarly drawn, but included by CA and CB.

We are to prove $CA + CB > OA + OB$.

Produce AO to meet the line CB at E.

Then $AC + CE > AO + OE$, § 18

(*a straight line is the shortest distance between two points*),

and $BE + OE > BO$. § 18

Add these inequalities, and we have

$$CA + CE + BE + OE > OA + OE + OB.$$

Substitute for $CE + BE$ its equal CB,

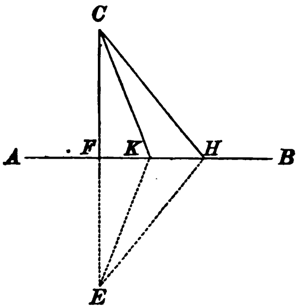
and take away OE from each side of the inequality.

We have $CA + CB > OA + OB$.

Q. E. D.

Proposition VI. Theorem.

55. *Of two oblique lines drawn from the same point in a perpendicular, cutting off unequal distances from the foot of the perpendicular, the more remote is the greater.*



Let CF be perpendicular to AB, and CK and CH two oblique lines cutting off unequal distances from F.

We are to prove $CH > CK$.

Produce CF to E, *making* $FE = CF$.

Draw EK and EH.

$CH = HE$, and $CK = KE$, § 53

(*two oblique lines drawn from the same point in a* $\perp$, *cutting off equal distances from the foot of the* $\perp$, *are equal*).

But $CH + HE > CK + KE$, § 54

(*The sum of two oblique lines drawn from a point to the extremities of a straight line is greater than the sum of two other lines similarly drawn, but included by them*);

$$\therefore 2\,CH > 2\,CK;$$

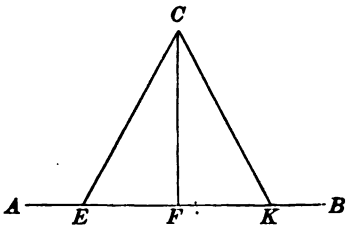
$$\therefore CH > CK.$$

Q. E. D.

56. Corollary. Only two equal straight lines can be drawn from a point to a straight line; and of two unequal lines, the greater cuts off the greater distance from the foot of the perpendicular.

Proposition VII. Theorem.

57. *Two equal oblique lines, drawn from the same point in a perpendicular, cut off equal distances from the foot of the perpendicular.*



Let CF be the perpendicular, and CE and CK be two equal oblique lines drawn from the point C.

We are to prove $FE = FK$.

Fold over CFA on CF as an axis, until it comes into the plane of CFB.

The line FE will take the direction FK,
($\angle CFE = \angle CFK$, *each being a rt.* $\angle$).

Then the point E must fall upon the point K;

otherwise one of these oblique lines must be more remote from the $\perp$,

and $\therefore$ greater than the other; which is contrary to the hypothesis. § 55

$\therefore FE = FK$.

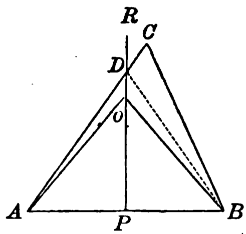
Q. E. D.

PROPOSITION VIII. THEOREM.

58. *If at the middle point of a straight line a perpendicular be erected,*

I. *Any point in the perpendicular is at equal distances from the extremities of the straight line.*

II. *Any point without the perpendicular is at unequal distances from the extremities of the straight line.*



Let PR be a perpendicular erected at the middle of the straight line AB, O any point in PR, and C any point without PR.

I. Draw OA and OB.

We are to prove $OA = OB$.

Since $PA = PB$,

$OA = OB$, § 53

(*two oblique lines drawn from the same point in a* $\perp$, *cutting off equal distances from the foot of the* $\perp$, *are equal*).

II. Draw CA and CB.

We are to prove CA *and* CB *unequal.*

One of these lines, as CA, will intersect the $\perp$.

From D, the point of intersection, draw DB.

$$DB = DA, \qquad \S\ 53$$

(*two oblique lines drawn from the same point in a* $\perp$, *cutting off equal distances from the foot of the* $\perp$, *are equal*).

$$CB < CD + DB, \qquad \S\ 18$$

(*a straight line is the shortest distance between two points*).

Substitute for DB its equal DA, then

$$CB < CD + DA.$$

But $$CD + DA = CA, \qquad \text{Ax. 9.}$$

$$\therefore CB < CA.$$

Q. E. D.

59. The *Locus of a point* is a line, straight or curved, containing all the points which possess a common property.

Thus, the perpendicular erected at the middle of a straight line is the locus of all points equally distant from the extremities of that straight line.

60. SCHOLIUM. Since two points determine the position of a straight line, two points equally distant from the extremities of a straight line determine the perpendicular at the middle point of that line.

Ex. 1. If an angle be a right angle, what is its complement?

2. If an angle be a right angle, what is its supplement?

3. If an angle be $\frac{2}{3}$ of a right angle, what is its complement?

4. If an angle be $\frac{2}{3}$ of a right angle, what is its supplement?

5. Show that the bisectors of two vertical angles form one and the same straight line.

6. Show that the two straight lines which bisect the two pairs of vertical angles are perpendicular to each other.

PROPOSITION IX. THEOREM.

61. *At a point in a straight line only one perpendicular to that line can be drawn; and from a point without a straight line only one perpendicular to that line can be drawn.*

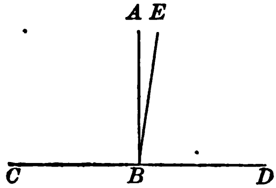


Fig. 1.

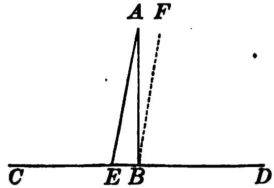


Fig. 2.

Let BA (fig. 1) be perpendicular to CD at the point B.

We are to prove BA the only perpendicular to CD at the point B.

If it be possible, let BE be another line $\perp$ to CD at B.

Then $\angle EBD$ is a rt. $\angle$. § 26

But $\angle ABD$ is a rt. $\angle$. § 26

$\therefore \angle EBD = \angle ABD$. Ax. 1.

That is, a part is equal to the whole; which is impossible.

In like manner it may be shown that no other line but BA is $\perp$ to CD at B.

Let AB (fig. 2) be perpendicular to CD from the point A.

We are to prove AB the only $\perp$ to CD from the point A.

If it be possible, let AE be another line drawn from A $\perp$ to CD.

Conceive $\angle AEB$ to be moved to the right until the vertex E falls on B, the side EB continuing in the line CD.

Then the line EA will take the position BF.

Now if AE be $\perp$ to CD, BF is $\perp$ to CD, and there will be two $\perp$s to CD at the point B; which is impossible.

In like manner, it may be shown that no other line but AB is $\perp$ to CD from A. Q. E. D.

62. COROLLARY. Two lines in the same plane perpendicular to the same straight line have the same direction; otherwise they would meet (§ 22), and we should have two perpendicular lines drawn from their point of meeting to the same line; which is impossible.

On Parallel Lines.

63. *Parallel Lines* are straight lines which lie in the same plane and have the same direction, or opposite directions.

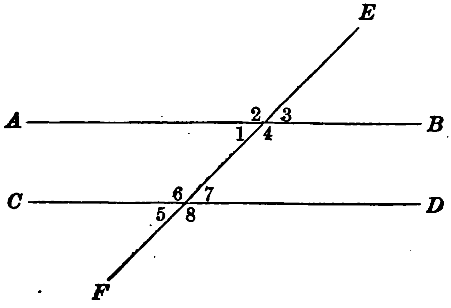
Parallel lines lie in the same direction, when they are on the same side of the straight line joining their origins.

Parallel lines lie in opposite directions, when they are on opposite sides of the straight line joining their origins.

64. *Two parallel lines cannot meet.* § 21

65. *Two lines in the same plane perpendicular to a given line have the same direction* (§ 62), *and are therefore parallel.*

66. *Through a given point only one line can be drawn parallel to a given line.* § 18



If a straight line EF cut two other straight lines AB and CD, it makes with those lines eight angles, to which particular names are given.

The angles 1, 4, 6, 7 are called *Interior* angles.

The angles 2, 3, 5, 8 are called *Exterior* angles.

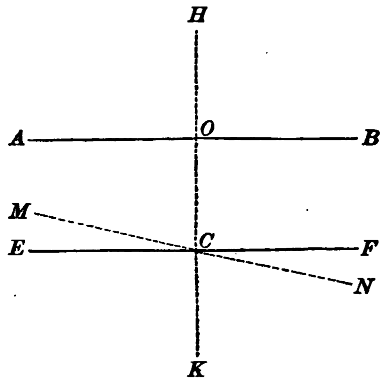
The pairs of angles 1 and 7, 4 and 6 are called *Alternate-interior* angles.

The pairs of angles 2 and 8, 3 and 5 are called *Alternate-exterior* angles.

The pairs of angles 1 and 5, 2 and 6, 4 and 8, 3 and 7 are called *Exterior-interior* angles.

PROPOSITION X. THEOREM.

67. *If a straight line be perpendicular to one of two parallel lines, it is perpendicular to the other.*



Let $A B$ and $E F$ be two parallel lines, and let $H K$ be perpendicular to $A B$.

We are to prove $H K \perp$ *to* $E F$.

Through C draw $M N \perp$ to $H K$.

Then $M N$ is $\parallel$ to $A B$. § 65

(*Two lines in the same plane* $\perp$ *to a given line are parallel*).

But $E F$ is $\parallel$ to $A B$, Hyp.

$\therefore E F$ coincides with $M N$. § 66

(*Through the same point only one line can be drawn* $\parallel$ *to a given line*).

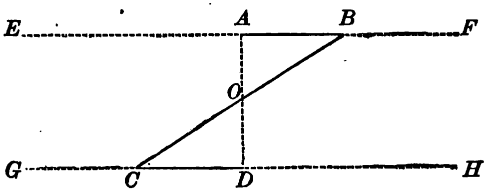
$\therefore E F$ is $\perp$ to $H K$,

that is $H K$ is $\perp$ to $E F$.

Q. E. D.

PROPOSITION XI. THEOREM.

68. *If two parallel straight lines be cut by a third straight line the alternate-interior angles are equal.*



Let EF and GH be two parallel straight lines cut by the line BC.

We are to prove $\angle B = \angle C$.

Through O, the middle point of BC, draw $AD \perp$ to GH.

Then AD is likewise $\perp$ to EF, § 67

(*a straight line $\perp$ to one of two $\parallel$s is $\perp$ to the other*),

that is, CD and BA are both $\perp$ to AD.

Apply figure COD to figure BOA so that OD shall fall on OA.

Then OC will fall on OB,

(*since $\angle COD = \angle BOA$, being vertical* ∡);

and point C will fall upon B,

(*since $OC = OB$ by construction*).

Then $\perp CD$ will coincide with $\perp BA$, § 61

(*from a point without a straight line only one $\perp$ to that line can be drawn*).

$\therefore \angle OCD$ coincides with $\angle OBA$, and is equal to it.

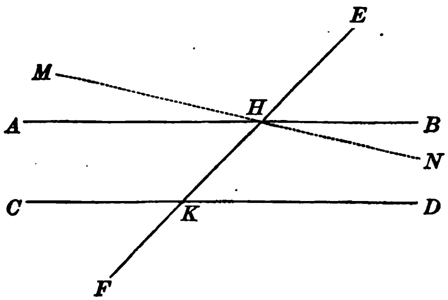
Q. E. D.

SCHOLIUM. By the *converse* of a proposition is meant a proposition which has the hypothesis of the first as conclusion and the conclusion of the first as hypothesis. The converse of a truth is not *necessarily* true. Thus, *parallel lines never meet;* its converse, *lines which never meet are parallel,* is not true unless the lines lie in the same plane.

NOTE. — The converse of many propositions will be omitted, but their statement and demonstration should be required as an important exercise for the student.

PROPOSITION XII. THEOREM.

69. CONVERSELY: *When two straight lines are cut by a third straight line, if the alternate-interior angles be equal, the two straight lines are parallel.*



Let EF cut the straight lines AB and CD in the points H and K, and let the $\angle AHK = \angle HKD$.

We are to prove $AB \parallel$ *to* CD.

Through the point H draw $MN \parallel$ to CD;

then $\angle MHK = \angle HKD$, § 68

(*being alt.-int.* $\angle$s).

But $\angle AHK = \angle HKD$, Hyp.

$\therefore \angle MHK = \angle AHK$. Ax. 1.

$\therefore$ the lines MN and AB coincide.

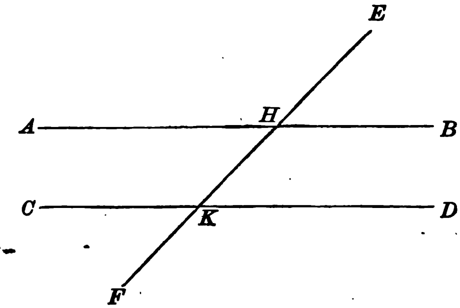
But MN is $\parallel$ to CD; Cons.

$\therefore AB$, which coincides with MN, is $\parallel$ to CD.

Q. E. D.

PROPOSITION XIII. THEOREM.

70. *If two parallel lines be cut by a third straight line, the exterior-interior angles are equal.*



Let AB and CD be two parallel lines cut by the straight line EF, in the points H and K.

We are to prove $\angle EHB = \angle HKD$.

$\angle EHB = \angle AHK$, § 49
(being vertical $\angle$s*).*

But $\angle AHK = \angle HKD$, § 68
(being alt.-int. $\angle$s*).*

$\therefore \angle EHB = \angle HKD$. Ax. 1

In like manner we may prove

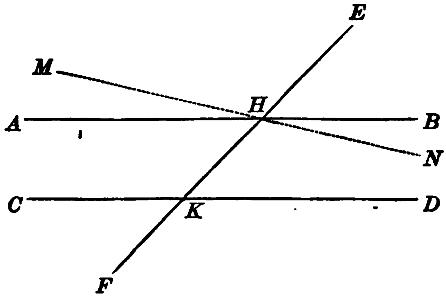
$$\angle EHA = \angle HKC.$$

Q. E. D.

71. COROLLARY. The alternate-exterior angles, EHB and CKF, and also AHE and DKF, are equal.

Proposition XIV. Theorem.

72. Conversely: *When two straight lines are cut by a third straight line, if the exterior-interior angles be equal, these two straight lines are parallel.*



Let EF cut the straight lines AB and CD in the points H and K, and let the $\angle EHB = \angle HKD$.

We are to prove $AB \parallel$ *to* CD.

Through the *point* H draw the straight line $MN \parallel$ to CD.

Then $\angle EHN = \angle HKD$, § 70
(*being ext.-int.* $\angle$s).

But $\angle EHB = \angle HKD$. Hyp.

$\therefore \angle EHB = \angle EHN$. Ax. 1.

$\therefore$ the lines MN and AB coincide.

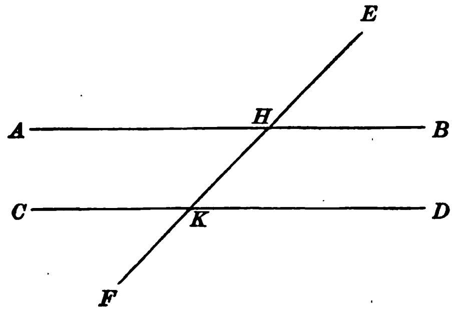
But MN is $\parallel$ to CD, Cons.

$\therefore AB$, which coincides with MN, is $\parallel$ to CD.

Q. E. D.

Proposition XV. Theorem.

73. *If two parallel lines be cut by a third straight line, the sum of the two interior angles on the same side of the secant line is equal to two right angles.*



Let AB and CD be two parallel lines cut by the straight line EF in the points H and K.

We are to prove $\angle BHK + \angle HKD =$ *two rt.* $\angle s$.

$$\angle EHB + \angle BHK = 2 \text{ rt. } \angle s, \qquad \S\ 34$$

(being sup.-adj. $\angle s$*).*

But $\angle EHB = \angle HKD$, § 70

(being ext.-int. $\angle s$*).*

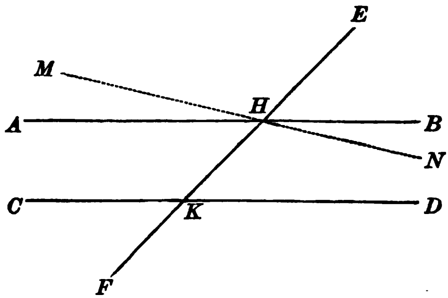
Substitute $\angle HKD$ for $\angle EHB$ in the first equality;

then $\angle BHK + \angle HKD = 2$ rt. $\angle s$.

Q. E. D.

PROPOSITION XVI. THEOREM.

74. CONVERSELY: *When two straight lines are cut by a third straight line, if the two interior angles on the same side of the secant line be together equal to two right angles, then the two straight lines are parallel.*



Let EF cut the straight lines AB and CD in the points H and K, and let the $\angle BHK + \angle HKD$ equal two right angles.

We are to prove $AB \parallel$ *to* CD.

Through the point H draw $MN \parallel$ to CD.

Then $\angle NHK + \angle HKD = 2$ rt. $\angle$s, § 73

(being two interior $\angle$s on the same side of the secant line).

But $\angle BHK + \angle HKD = 2$ rt. $\angle$s. Hyp.

$\therefore \angle NHK + \angle HKD = \angle BHK + \angle HKD$. Ax. 1.

Take away from each of these equals the common $\angle HKD$,

then $\angle NHK = \angle BHK$.

$\therefore$ the lines AB and MN coincide.

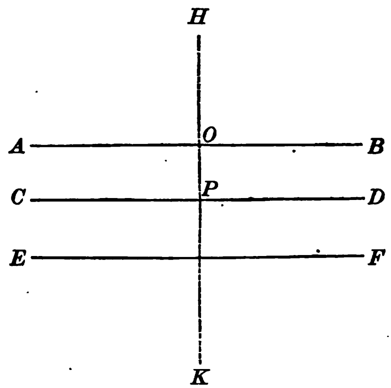
But MN is $\parallel$ to CD; Cons.

$\therefore AB$, which coincides with MN, is $\parallel$ to CD.

Q. E. D.

Proposition XVII. Theorem.

75. *Two straight lines which are parallel to a third straight line are parallel to each other.*



Let AB and CD be parallel to EF.

We are to prove $AB \parallel$ *to* CD.

Draw $HK \perp$ to EF.

Since CD and EF are $\parallel$, HK is $\perp$ to CD, § 67

(if a straight line be $\perp$ to one of two $\parallel$s, it is $\perp$ to the other also).

Since AB and EF are $\parallel$, HK is also $\perp$ to AB, § 67

$\therefore \angle HOB = \angle HPD$,

(each being a rt. $\angle$).

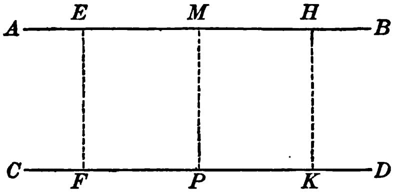
$\therefore AB$ is $\parallel$ to CD, § 72

(when two straight lines are cut by a third straight line, if the ext.-int. $\angle$s be equal, the two lines are $\parallel$).

Q. E. D.

PROPOSITION XVIII. THEOREM.

76. *Two parallel lines are everywhere equally distant from each other.*



Let AB and CD be two parallel lines, and from any two points in AB, as E and H, let EF and HK be drawn perpendicular to AB.

We are to prove $EF = HK$.

Now EF and HK are $\perp$ to CD, § 67

(a line $\perp$ to one of two $\parallel$s is $\perp$ to the other also).

Let M be the middle point of EH.

Draw $MP \perp$ to AB.

On MP as an axis, fold over the portion of the figure on the right of MP until it comes into the plane of the figure on the left.

MB will fall on MA,

(for $\angle PMH = \angle PME$, each being a rt. $\angle$);

the point H will fall on E,

(for $MH = ME$, by hyp.);

HK will fall on EF,

(for $\angle MHK = \angle MEF$, each being a rt. $\angle$);

and the point K will fall on EF, or EF produced.

Also, PD will fall on PC,

($\angle MPK = \angle MPF$, each being a rt. $\angle$);

and the point K will fall on PC.

Since the point K falls in both the lines EF and PC, it must fall at their point of intersection F.

$\therefore HK = EF$, § 18

(their extremities being the same points).

Q. E. D.

PROPOSITION XIX. THEOREM.

77. *Two angles whose sides are parallel, two and two, and lie in the same direction, or opposite directions, from their vertices, are equal.*

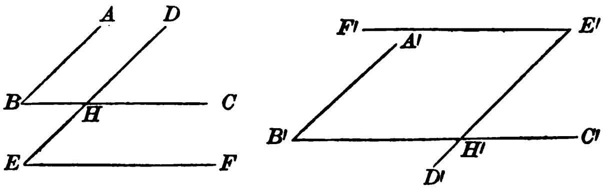


Fig. 1. Fig. 2.

Let △ B and E (Fig. 1) have their sides BA and ED, and BC and EF respectively, parallel and lying in the same direction from their vertices.

We are to prove the $\angle B = \angle E$.

Produce (if necessary) two sides which are not ∥ until they intersect, as at H;

then $\angle B = \angle DHC$, § 70
(*being ext.-int.* △),

and $\angle E = \angle DHC$, § 70

$\therefore \angle B = \angle E$. Ax. 1

Let △ B′ and E′ (Fig. 2) have $B'A'$ and $E'D'$, and $B'C'$ and $E'F'$ respectively, parallel and lying in opposite directions from their vertices.

We are to prove the $\angle B' = \angle E'$.

Produce (if necessary) two sides which are not ∥ until they intersect, as at H'.

Then $\angle B' = \angle E'H'C'$, § 70
(*being ext.-int.* △),

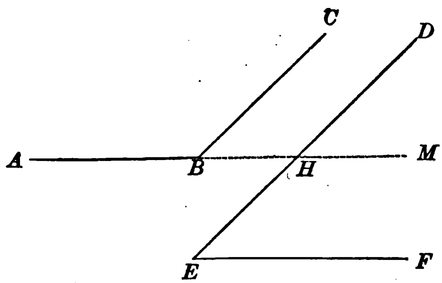
and $\angle E' = \angle E'H'C'$, § 68
(*being alt.-int.* △);

$\therefore \angle B' = \angle E'$, Ax. 1.

Q. E. D.

Proposition XX. Theorem.

78. *If two angles have two sides parallel and lying in the same direction from their vertices, while the other two sides are parallel and lie in opposite directions, then the two angles are supplements of each other.*



Let A B C and D E F be two angles having B C and E D parallel and lying in the same direction from their vertices, while E F and B A are parallel and lie in opposite directions.

We are to prove $\angle ABC$ *and* $\angle DEF$ *supplements of each other.*

Produce (if necessary) two sides which are not ∥ until they intersect as at H.

$\angle ABC = \angle BHD$, § 70
(*being ext.-int.* $\measuredangle$s).

$\angle DEF = \angle BHE$, § 68
(*being alt.-int.* $\measuredangle$s).

But $\angle BHD$ and $\angle BHE$ are supplements of each other, § 34
(*being sup.-adj.* $\measuredangle$s).

$\therefore \angle ABC$ and $\angle DEF$, the equals of $\angle BHD$ and $\angle BHE$, are supplements of each other.

Q. E. D.

ON TRIANGLES.

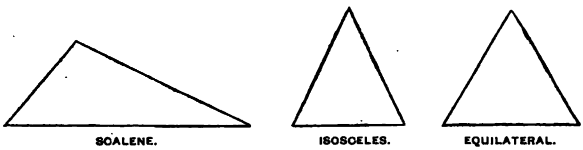
79. Def. A *Triangle* is a plane figure bounded by three straight lines.

A triangle has six parts, three sides and three angles.

80. When the six parts of one triangle are equal to the six parts of another triangle, each to each, the triangles are said to be *equal in all respects.*

81. Def. In two equal triangles, the equal angles are called *Homologous* angles, and the equal sides are called *Homologous* sides.

82. In equal triangles the equal sides are opposite the equal angles.



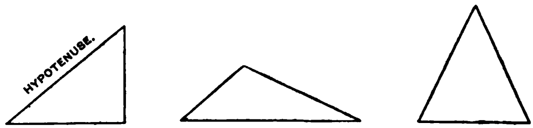
83. Def. A *Scalene* triangle is one of which no two sides are equal.

84. Def. An *Isosceles* triangle is one of which two sides are equal.

85. Def. An *Equilateral* triangle is one of which the three sides are equal.

86. Def. The *Base* of a triangle is the side on which the triangle is supposed to stand.

In an isosceles triangle, the side which is not one of the equal sides is considered the base.



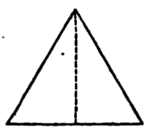
RIGHT. OBTUSE. ACUTE.

87. Def. A *Right* triangle is one which has one of the angles a right angle.

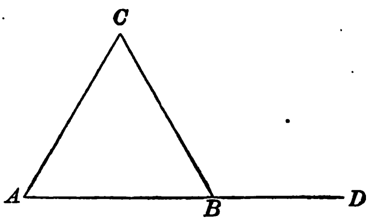
88. Def. The side opposite the right angle is called the *Hypotenuse.*

89. Def. An *Obtuse* triangle is one which has one of the angles an obtuse angle.

90. Def. An *Acute* triangle is one which has all the angles acute.



EQUIANGULAR.



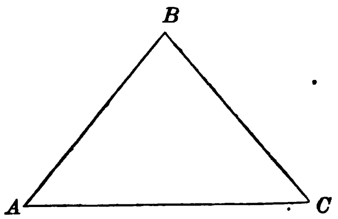
91. Def. An *Equiangular* triangle is one which has all the angles equal.

92. Def. In any triangle, the angle opposite the base is called the *Vertical* angle, and its vertex is called the *Vertex* of the triangle.

93. Def. The *Altitude* of a triangle is the perpendicular distance from the vertex to the base, or the base produced.

94. Def. The *Exterior* angle of a triangle is the angle included between a side and an adjacent side produced, as $\angle CBD$.

95. Def. The two angles of a triangle which are opposite the exterior angle, are called the two *opposite interior* angles, as $\angle$s A and C.



96. *Any side of a triangle is less than the sum of the other two sides.*

Since a straight line is the shortest distance between two points,

$$AC < AB + BC.$$

97. *Any side of a triangle is greater than the difference of the other two sides.*

In the inequality $AC < AB + BC$,

take away AB from each side of the inequality.

Then $$AC - AB < BC; \text{ or}$$

$$BC > AC - AB.$$

Ex. 1. Show that the sum of the distances of any point in a triangle from the vertices of three angles of the triangle is greater than half the sum of the sides of the triangle.

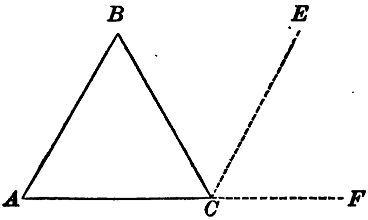
2. Show that the *locus* of all the points at a given distance from a given straight line AB consists of two parallel lines, drawn on opposite sides of AB, and at the given distance from it.

3. Show that the two equal straight lines drawn from a point to a straight line make equal acute angles with that line.

4. Show that, if two angles have their sides perpendicular, each to each, they are either equal or supplementary.

PROPOSITION XXI. THEOREM.

98. *The sum of the three angles of a triangle is equal to two right angles.*



Let $A B C$ be a triangle.

We are to prove $\angle B + \angle BCA + \angle A =$ *two rt.* $\angle$s.

Draw $CE \parallel$ to AB, and prolong AC.

Then $\angle ECF + \angle ECB + \angle BCA = 2$ rt. $\angle$s, § 34
(the sum of all the $\angle$s about a point on the same side of a straight line $= 2$ rt. $\angle$s).

But $\angle A = \angle ECF$, § 70
(being ext.-int. $\angle$s),

and $\angle B = \angle BCE$, § 68
(being alt.-int. $\angle$s).

Substitute for $\angle ECF$ and $\angle BCE$ their equal $\angle$s, A and B.

Then $\angle A + \angle B + \angle BCA = 2$ rt. $\angle$s.

Q. E. D.

99. COROLLARY 1. If the sum of two angles of a triangle be known, the third angle can be found by taking this sum from two right angles.

100. COR. 2. If two triangles have two angles of the one equal to two angles of the other, the third angles will be equal.

101. Cor. 3. If two right triangles have an acute angle of the one equal to an acute angle of the other, the other acute angles will be equal.

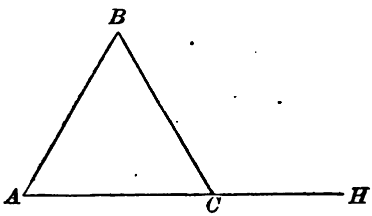
102. Cor. 4. In a triangle there can be but one right angle, or one obtuse angle.

103. Cor. 5. In a right triangle the two acute angles are complements of each other.

104. Cor. 6. In an equiangular triangle, each angle is one third of two right angles, or two thirds of one right angle.

Proposition XXII. Theorem.

105. *The exterior angle of a triangle is equal to the sum of the two opposite interior angles.*



Let BCH be an exterior angle of the triangle ABC.

We are to prove $\angle BCH = \angle A + \angle B$.

$\angle BCH + \angle ACB = 2$ rt. $\angle$s, § 34
(being sup.-adj. $\angle$s).

$\angle A + \angle B + \angle ACB = 2$ rt. $\angle$s, § 98
(three $\angle$s of a $\triangle$ = two rt. $\angle$s).

$\therefore \angle BCH + \angle ACB = \angle A + \angle B + \angle ACB$. Ax. 1.

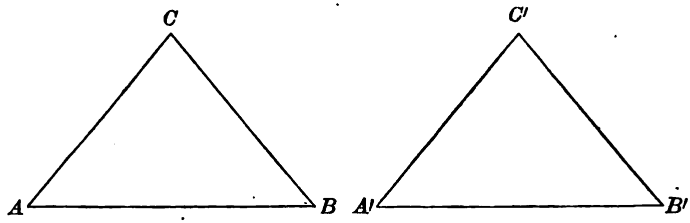
Take away from each of these equals the common $\angle ACB$;

then $\angle BCH = \angle A + \angle B$.

Q. E. D.

PROPOSITION XXIII. THEOREM.

106. *Two triangles are equal in all respects when two sides and the included angle of the one are equal respectively to two sides and the included angle of the other.*



In the triangles ABC and $A'B'C'$, let $AB = A'B'$, $AC = A'C'$, $\angle A = \angle A'$.

We are to prove $\triangle ABC = \triangle A'B'C'$.

Take up the $\triangle ABC$ and place it upon the $\triangle A'B'C'$ so that AB shall coincide with $A'B'$.

Then AC will take the direction of $A'C'$,
(*for* $\angle A = \angle A'$, *by hyp.*),

the point C will fall upon the point C',
(*for* $AC = A'C'$, *by hyp.*);

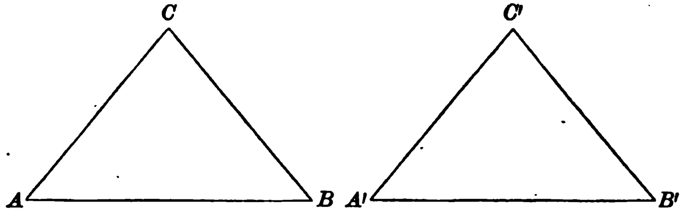
$\therefore CB = C'B'$, § 18
(*their extremities being the same points*).

$\therefore$ the two $\triangle$s coincide, and are equal in all respects.

Q. E. D.

Proposition XXIV. Theorem.

107. *Two triangles are equal in all respects when a side and two adjacent angles of the one are equal respectively to a side and two adjacent angles of the other.*



In the triangles ABC **and** $A'B'C'$, **let** $AB = A'B'$, $\angle A = \angle A'$, $\angle B = \angle B'$.

We are to prove $\triangle ABC = \triangle A'B'C'$.

Take up $\triangle ABC$ and place it upon $\triangle A'B'C'$, so that AB shall coincide with $A'B'$.

AC will take the direction of $A'C'$,
(*for* $\angle A = \angle A'$, *by hyp.*);

the point C, the extremity of AC, will fall upon $A'C'$ or $A'C'$ produced.

BC will take the direction of $B'C'$,
(*for* $\angle B = \angle B'$, *by hyp.*);

the point C, the extremity of BC, will fall upon $B'C'$ or $B'C'$ produced.

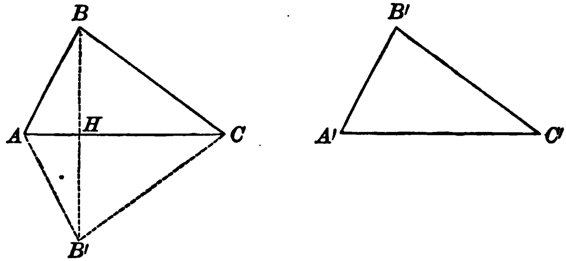
$\therefore$ the point C, falling upon both the lines $A'C'$ and $B'C'$, must fall upon a point common to the two lines, namely, C'.

$\therefore$ the two $\triangle$s coincide, and are equal in all respects.

Q. E. D.

Proposition XXV. Theorem.

108. *Two triangles are equal when the three sides of the one are equal respectively to the three sides of the other.*



In the triangles $A\,B\,C$ *and* $A'\,B'\,C'$, *let* $A\,B = A'\,B'$, $A\,C = A'\,C'$, $B\,C = B'\,C'$.

We are to prove $\triangle A\,B\,C = \triangle A'\,B'\,C'$.

Place $\triangle A'\,B'\,C'$ in the position $A\,B'\,C$, having its greatest side $A'\,C'$ in coincidence with its equal $A\,C$, and its vertex at B', opposite B.

Draw $B\,B'$ intersecting $A\,C$ at H.

Since $A\,B = A\,B'$, Hyp.

point A is at equal distances from B and B'.

Since $B\,C = B'\,C$, Hyp.

point C is at equal distances from B and B'.

$\therefore A\,C$ is $\perp$ to $B\,B'$ at its middle point, § 60

(*two points at equal distances from the extremities of a straight line determine the* $\perp$ *at the middle of that line*).

Now if $\triangle A\,B'\,C$ be folded over on $A\,C$ as an axis until it comes into the plane of $\triangle A\,B\,C$,

$H\,B'$ will fall on $H\,B$,

(*for* $\angle A\,H\,B = \angle A\,H\,B'$, *each being a rt.* $\angle$),

and point B' will fall on B,

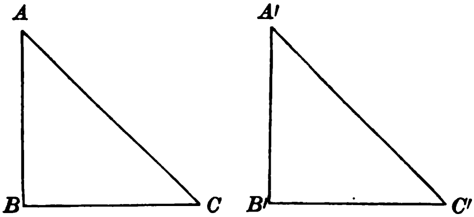
(*for* $H\,B' = H\,B$).

$\therefore$ the two $\triangle$ coincide, and are equal in all respects.

Q. E. D.

PROPOSITION XXVI. THEOREM.

109. *Two right triangles are equal when a side and the hypotenuse of the one are equal respectively to a side and the hypotenuse of the other.*



In the right triangles $A B C$ and $A' B' C'$, let $A B = A' B'$, and $A C = A' C'$.

We are to prove $\triangle A B C = \triangle A' B' C'$.

Take up the $\triangle A B C$ and place it upon $\triangle A' B' C'$, so that $A B$ will coincide with $A' B'$.

Then $B C$ will fall upon $B' C'$,

(for $\angle A B C = \angle A' B' C'$, each being a rt. $\angle$),

and point C will fall upon C';

otherwise the equal oblique lines $A C$ and $A' C'$ would cut off *unequal* distances from the foot of the $\perp$, which is impossible, § 57

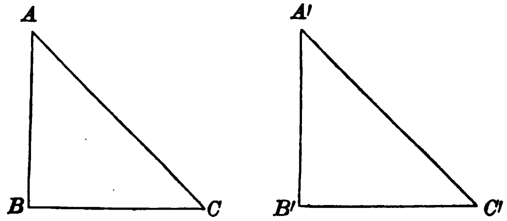
(two equal oblique lines from a point in a $\perp$ cut off equal distances from the foot of the $\perp$).

$\therefore$ the two $\triangle$s coincide, and are equal in all respects.

Q. E. D.

PROPOSITION XXVII. THEOREM.

110. *Two right triangles are equal when the hypotenuse and an acute angle of the one are equal respectively to the hypotenuse and an acute angle of the other.*



In the right triangles $A\,B\,C$ and $A'\,B'\,C'$, let $A\,C = A'\,C'$, and $\angle A = \angle A'$.

We are to prove $\triangle\,A\,B\,C = \triangle\,A'\,B'\,C'$.

$A\,C = A'\,C'$, Hyp.

$\angle A = \angle A'$, Hyp.

then $\angle C = \angle C'$, § 101

(if two rt. $\triangle$ have an acute $\angle$ of the one equal to an acute $\angle$ of the other, then the other acute $\angle$ are equal).

$\therefore \triangle\,A\,B\,C = \triangle\,A'\,B'\,C'$, § 107

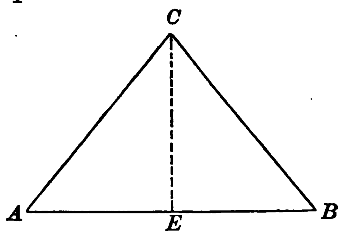
(two $\triangle$ are equal when a side and two adj. $\angle$ of the one are equal respectively to a side and two adj. $\angle$ of the other).

Q. E. D.

111. COROLLARY. Two right triangles are equal when a side and an acute angle of the one are equal respectively to an homologous side and acute angle of the other.

Proposition XXVIII. Theorem.

112. *In an isosceles triangle the angles opposite the equal sides are equal.*



Let ABC be an isosceles triangle, having the sides AC and CB equal.

We are to prove $\angle A = \angle B$.

From C draw the straight line CE so as to bisect the $\angle ACB$.

In the $\triangle$s ACE and BCE,

$AC = BC$, Hyp.

$CE = CE$, Iden.

$\angle ACE = \angle BCE$; Cons.

$\therefore \triangle ACE = \triangle BCE$, § 106

(two $\triangle$s are equal when two sides and the included $\angle$ of the one are equal respectively to two sides and the included $\angle$ of the other).

$\therefore \angle A = \angle B$,

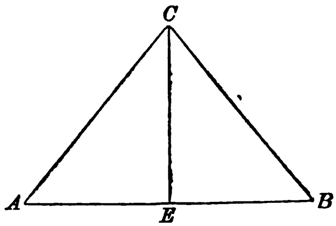
(being homologous $\angle$s of equal $\triangle$s).

Q. E. D.

Ex. If the equal sides of an isosceles triangle be produced, show that the angles formed with the base by the sides produced are equal.

PROPOSITION XXIX. THEOREM.

113. *A straight line which bisects the angle at the vertex of an isosceles triangle divides the triangle into two equal triangles, is perpendicular to the base, and bisects the base.*



Let the line CE bisect the $\angle ACB$ of the isosceles $\triangle ACB$.

We are to prove I. $\triangle ACE = \triangle BCE$;

II. *line* $CE \perp$ *to* AB;

III. $AE = BE$.

I. In the $\triangle$s ACE and BCE,

$AC = BC$, Hyp.

$CE = CE$, Iden.

$\angle ACE = \angle BCE$. Cons.

$\therefore \triangle ACE = \triangle BCE$, § 106

(*having two sides and the included $\angle$ of the one equal respectively to two sides and the included $\angle$ of the other*).

Also, II. $\angle CEA = \angle CEB$,

(*being homologous $\angle$s of equal $\triangle$s*).

$\therefore CE$ is $\perp$ to AB,

(*a straight line meeting another, making the adjacent $\angle$s equal, is $\perp$ to that line*).

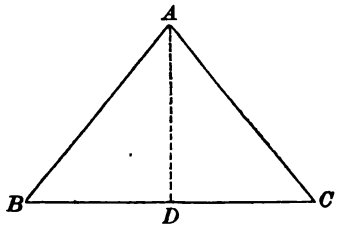
Also, III. $AE = EB$,

(*being homologous sides of equal $\triangle$s*).

Q. E. D.

PROPOSITION XXX. THEOREM.

114. *If two angles of a triangle be equal, the sides opposite the equal angles are equal, and the triangle is isosceles.*



In the triangle ABC, let the $\angle B = \angle C$.

We are to prove $AB = AC$.

Draw $AD \perp$ to BC.

In the rt. $\triangle$s ADB and ADC,

$AD = AD$, Iden.

$\angle B = \angle C$,

$\therefore$ rt. $\triangle ADB =$ rt. $\triangle ADC$, § 111

(having a side and an acute $\angle$ of the one equal respectively to a side and an acute $\angle$ of the other).

$\therefore AB = AC$,

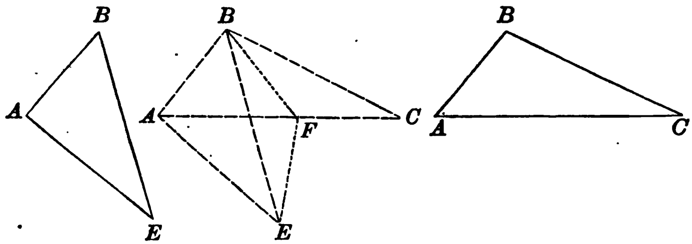
(being homologous sides of equal $\triangle$s).

Q. E. D.

Ex. Show that an equiangular triangle is also equilateral.

PROPOSITION XXXI. THEOREM.

115. *If two triangles have two sides of the one equal respectively to two sides of the other, but the included angle of the first greater than the included angle of the second, then the third side of the first will be greater than the third side of the second.*



In the $\triangle$ **ABC and ABE, let $AB = AB$, $BC = BE$; but $\angle ABC > \angle ABE$.**

We are to prove $AC > AE$.

Place the $\triangle$ so that AB of the one shall coincide with AB of the other.

Draw BF so as to bisect $\angle EBC$.

Draw EF.

In the $\triangle$ EBF and CBF

$EB = BC$, Hyp.

$BF = BF$, Iden.

$\angle EBF = \angle CBF$, Cons.

$\therefore$ the $\triangle$ EBF and CBF are equal, § 106

(*having two sides and the included $\angle$ of one equal respectively to two sides and the included $\angle$ of the other*).

$\therefore EF = FC$,

(*being homologous sides of equal* $\triangle$).

Now $AF + FE > AE$, § 96

(*the sum of two sides of a $\triangle$ is greater than the third side*).

Substitute for FE its equal FC. Then

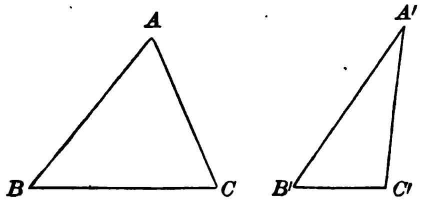
$AF + FC > AE$; or,

$AC > AE$.

Q. E. D.

Proposition XXXII. Theorem.

116. Conversely: *If two sides of a triangle be equal respectively to two sides of another, but the third side of the first triangle be greater than the third side of the second, then the angle opposite the third side of the first triangle is greater than the angle opposite the third side of the second.*



In the $\triangle s$ ABC **and** $A'B'C'$, **let** $AB = A'B'$, $AC = A'C'$; **but** $BC > B'C'$.

We are to prove $\angle A > \angle A'$.

If $\angle A = \angle A'$,

then would $\triangle ABC = \triangle A'B'C'$, § 106

(having two sides and the included $\angle$ *of the one equal respectively to two sides and the included* $\angle$ *of the other),*

and $BC = B'C'$,

(being homologous sides of equal $\triangle s$ *).*

And if $A < A'$,

then would $BC < B'C'$, § 115

(if two sides of a $\triangle$ *be equal respectively to two sides of another* $\triangle$*, but the included* $\angle$ *of the first be greater than the included* $\angle$ *of the second, the third side of the first will be greater than the third side of the second.)*

But both these conclusions are contrary to the hypothesis;

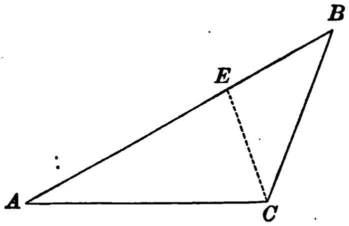
$\therefore \angle A$ does not equal $\angle A'$, and is not less than $\angle A'$.

$$\therefore \angle A > \angle A'.$$

Q. E. D

PROPOSITION XXXIII. THEOREM.

117. *Of two sides of a triangle, that is the greater which is opposite the greater angle.*



In the triangle ABC let angle ACB be greater than angle B.

We are to prove $AB > AC$.

Draw CE so as to make $\angle BCE = \angle B$.

Then $EC = EB$, § 114
(*being sides opposite equal* $\triangle$).

Now $AE + EC > AC$, § 96
(*the sum of two sides of a* $\triangle$ *is greater than the third side*).

Substitute for EC its equal EB. Then

$$AE + EB > AC, \text{ or}$$

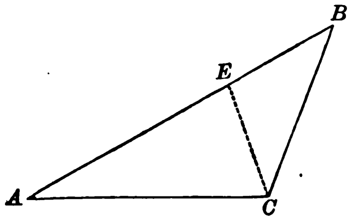
$$AB > AC.$$

Q. E. D.

Ex. ABC and ABD are two triangles on the same base AB, and on the same side of it, the vertex of each triangle being without the other. If AC equal AD, show that BC cannot equal BD.

PROPOSITION XXXIV. THEOREM.

118. *Of two angles of a triangle, that is the greater which is opposite the greater side.*



In the triangle ABC let AB be greater than AC.

We are to prove $\angle ACB > \angle B$.

Take AE equal to AC;

Draw EC.

$\angle AEC = \angle ACE$, § 112

(being $\angle$s opposite equal sides).

But $\angle AEC > \angle B$, § 105

(an exterior $\angle$ of a $\triangle$ is greater than either opposite interior $\angle$),

and $\angle ACB > \angle ACE$.

Substitute for $\angle ACE$ its equal $\angle AEC$, then

$\angle ACB > \angle AEC$.

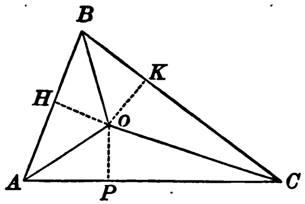
Much more is $\angle ACB > \angle B$.

Q. E. D.

Ex. If the angles ABC and ACB, at the base of an isosceles triangle, be bisected by the straight lines BD, CD, show that DBC will be an isosceles triangle.

PROPOSITION XXXV. THEOREM.

119. *The three bisectors of the three angles of a triangle meet in a point.*



Let the two bisectors of the angles A and C meet at O, and OB be drawn.

We are to prove BO *bisects the* $\angle B$.

Draw the $\perp$s OK, OP, and OH.

In the rt. $\triangle$s OCK and OCP,

$OC = OC$, Iden.

$\angle OCK = \angle OCP$, Cons.

$\therefore \triangle OCK = \triangle OCP$, § 110

(*having the hypotenuse and an acute $\angle$ of the one equal respectively to the hypotenuse and an acute $\angle$ of the other*).

$\therefore OP = OK$,

(*homologous sides of equal $\triangle$s*).

In the rt. $\triangle$s OAP and OAH,

$OA = OA$, Iden.

$\angle OAP = \angle OAH$, Cons.

$\therefore \triangle OAP = \triangle OAH$, § 110

(*having the hypotenuse and an acute $\angle$ of the one equal respectively to the hypotenuse and an acute $\angle$ of the other*).

$\therefore OP = OH$,

(*being homologous sides of equal $\triangle$s*).

But we have already shown $OP = OK$,

$\therefore OH = OK$, Ax. 1

Now in rt. $\triangle$s OHB and OKB

$$O H = O K, \text{ and } O B = O B,$$

$$\therefore \triangle O H B = \triangle O K B, \qquad \S\ 109$$

(*having the hypotenuse and a side of the one equal respectively to the hypotenuse and a side of the other*),

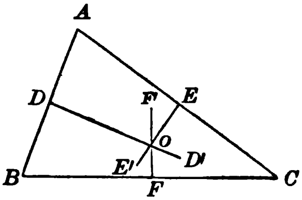
$$\therefore \angle O B H = \angle O B K,$$

(*being homologous* $\angle$s *of equal* $\triangle$s).

Q. E. D.

PROPOSITION XXXVI. THEOREM.

120. *The three perpendiculars erected at the middle points of the three sides of a triangle meet in a point.*



Let $D D'$, $E E'$, $F F'$, be three perpendiculars erected at D, E, F, the middle points of $A B$, $A C$, and $B C$.

We are to prove they meet in some point, as O.

The two $\perp$s $D D'$ and $E E'$ meet, otherwise they would be parallel, and $A B$ and $A C$, being $\perp$s to these lines from the same point A, would be in the same straight line;

but this is impossible, since they are sides of a $\triangle$.

Let O be the point at which they meet.

Then, since O is in $D D'$, which is $\perp$ to $A B$ at its middle point, it is equally distant from A and B. § 59

Also, since O is in $E E'$, $\perp$ to $A C$ at its middle point, it is equally distant from A and C.

$$\therefore O \text{ is equally distant from } B \text{ and } C;$$

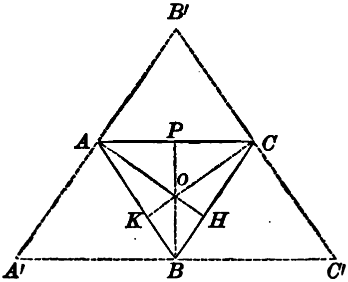
$$\therefore O \text{ is in } F F' \perp \text{ to } B C \text{ at its middle point}, \qquad \S\ 59$$

(*the locus of all points equally distant from the extremities of a straight line is the $\perp$ erected at the middle of that line*).

Q. E. D.

PROPOSITION XXXVII. THEOREM.

121. *The three perpendiculars from the vertices of a triangle to the opposite sides meet in a point.*



In the triangle ABC, let BP, AH, CK, be the perpendiculars from the vertices to the opposite sides.

We are to prove they meet in some point, as O.

Through the vertices A, B, C, draw

$$A'B' \parallel \text{ to } BC,$$
$$A'C' \parallel \text{ to } AC,$$
$$B'C' \parallel \text{ to } AB.$$

In the $\triangle$s ABA' and ABC, we have

$$AB = AB, \qquad \text{Iden.}$$

$$\angle ABA' = \angle BAC, \qquad \S\ 68$$

(being alternate interior $\angle$s),

$$\angle BAA' = \angle ABC. \qquad \S\ 68$$

$$\therefore \triangle ABA' = \triangle ABC, \qquad \S\ 107$$

(having a side and two adj. $\angle$s of the one equal respectively to a side and two adj. $\angle$s of the other).

$$\therefore A'B = AC,$$

(being homologous sides of equal $\triangle$s).

In the $\triangle s$ CBC' and ABC,

$$BC = BC, \qquad \text{Iden.}$$

$$\angle CBC' = \angle BCA, \qquad \S\ 68$$

(being alternate interior $\angle s$*).*

$$\angle BCC' = \angle CBA. \qquad \S\ 68$$

$$\therefore \triangle CBC' = \triangle ABC, \qquad \S\ 107$$

(having a side and two adj. $\angle s$ *of the one equal respectively to a side and two adj.* $\angle s$ *of the other).*

$$\therefore BC' = AC,$$

(being homologous sides of equal $\triangle s$*).*

But we have already shown $A'B = AC$,

$$\therefore A'B = BC', \qquad \text{Ax. 1.}$$

$\therefore B$ is the middle point of $A'C'$.

Since BP is $\perp$ to AC, Hyp.

it is $\perp$ to $A'C'$, § 67

(a straight line which is $\perp$ *to one of two* $\parallel$*s is* $\perp$ *to the other also).*

But B is the middle point of $A'C'$;

$\therefore BP$ is $\perp$ to $A'C'$ at its middle point.

In like manner we may prove that

AH is $\perp$ to $A'B'$ at its middle point,

and $CK \perp$ to $B'C'$ at its middle point.

$\therefore BP$, AH, and CK are $\perp$s erected at the middle points of the sides of the $\triangle A'B'C'$.

$\therefore$ these $\perp$s meet in a point. § 120

(the three $\perp$*s erected at the middle points of the sides of a* $\triangle$ *meet in a point).*

Q. E. D.

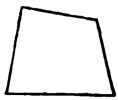
On Quadrilaterals.

122. Def. A *Quadrilateral* is a plane figure bounded by four straight lines.

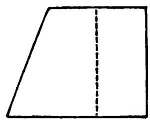
123. Def. A *Trapezium* is a quadrilateral which has no two sides parallel.

124. Def. A *Trapezoid* is a quadrilateral which has two sides parallel.

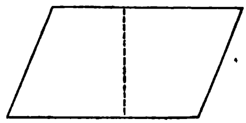
125. Def. A *Parallelogram* is a quadrilateral which has its opposite sides parallel.



TRAPEZIUM.



TRAPEZOID.



PARALLELOGRAM.

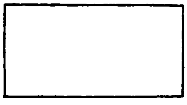
126. Def. A *Rectangle* is a parallelogram which has its angles right angles.

127. Def. A *Square* is a parallelogram which has its angles right angles, and its sides equal.

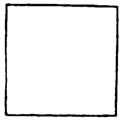
128. Def. A *Rhombus* is a parallelogram which has its sides equal, but its angles oblique angles.

129. Def. A *Rhomboid* is a parallelogram which has its angles oblique angles.

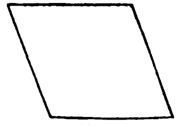
The figure marked parallelogram is also a rhomboid.



RECTANGLE.



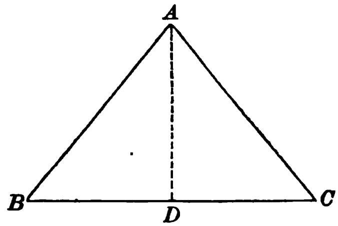
SQUARE.



RHOMBUS.

PROPOSITION XXX. THEOREM.

114. *If two angles of a triangle be equal, the sides opposite the equal angles are equal, and the triangle is isosceles.*



In the triangle ABC, ***let the*** $\angle B = \angle C$.

We are to prove $AB = AC$.

Draw $AD \perp$ to BC.

In the rt. $\triangle$s ADB and ADC,

$$AD = AD, \qquad \text{Iden.}$$

$$\angle B = \angle C,$$

$$\therefore \text{rt. } \triangle ADB = \text{rt. } \triangle ADC, \qquad \S\ 111$$

(having a side and an acute ∠ of the one equal respectively to a side and an acute ∠ of the other).

$$\therefore AB = AC,$$

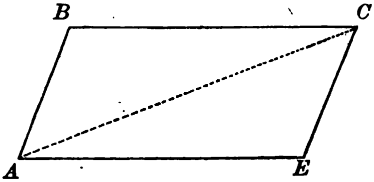
(being homologous sides of equal △s).

Q. E. D.

Ex. Show that an equiangular triangle is also equilateral.

PROPOSITION XXXIX. THEOREM.

134. *In a parallelogram the opposite sides are equal, and the opposite angles are equal.*



Let the figure $ABCE$ be a parallelogram.

We are to prove $BC = AE$, *and* $AB = EC$,

also, $\angle B = \angle E$, *and* $\angle BAE = \angle BCE$.

Draw AC.

$\triangle ABC = \triangle AEC$, § 133

(the diagonal of a ▱ divides the figure into two equal △s).

$\therefore BC = AE$,

and $AB = CE$,

(being homologous sides of equal △s).

$\angle B = \angle E$,

(being homologous ∠s of equal △s).

$\angle BAC = \angle ACE$,

and $\angle EAC = \angle ACB$,

(being homologous ∠s of equal △s).

Add these last two equalities, and we have

$$\angle BAC + \angle EAC = \angle ACE + \angle ACB;$$

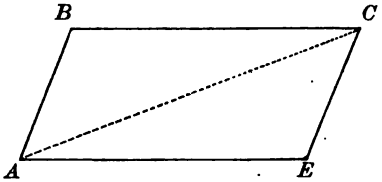
or, $\angle BAE = \angle BCE$.

Q. E. D.

135. COROLLARY. Parallel lines comprehended between parallel lines are equal.

Proposition XL. Theorem.

136. *If a quadrilateral have two sides equal and parallel, then the other two sides are equal and parallel, and the figure is a parallelogram.*



Let the figure $ABCE$ be a quadrilateral, having the side AE equal and parallel to BC.

We are to prove AB *equal and* $\parallel$ *to* EC.

Draw AC.

In the $\triangle$s ABC and AEC

$BC = AE$, Hyp.

$AC = AC$, Iden.

$\angle BCA = \angle CAE$, § 68

(being alt.-int. $\angle$s).

$\therefore \triangle ABC = \triangle ACE$, § 106

(having two sides and the included $\angle$ of the one equal respectively to two sides and the included $\angle$ of the other).

$\therefore AB = EC$,

(being homologous sides of equal $\triangle$s).

Also, $\angle BAC = \angle ACE$,

(being homologous $\angle$s of equal $\triangle$s);

$\therefore AB$ is $\parallel$ to EC, § 69

(when two straight lines are cut by a third straight line, if the alt.-int. $\angle$s be equal the lines are parallel).

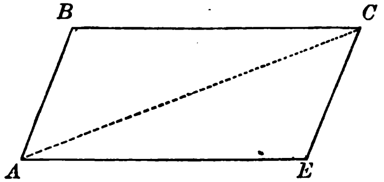
$\therefore$ the figure $ABCE$ is a $\square$, § 125

(the opposite sides being parallel).

Q. E. D.

PROPOSITION XLI. THEOREM.

137. *If in a quadrilateral the opposite sides be equal, the figure is a parallelogram.*



Let the figure $A B C E$ be a quadrilateral having $BC = A E$ and $A B = E C$.

We are to prove figure $A B C E$ a ▱.

Draw $A C$.

In the ⊿s $A B C$ and $A E C$

$B C = A E$, Hyp.

$A B = C E$, Hyp.

$A C = A C$, Iden.

$\therefore \triangle A B C = \triangle A E C$, § 108

(having three sides of the one equal respectively to three sides of the other).

$\therefore \angle A C B = \angle C A E$,

and $\angle B A C = \angle A C E$,

(being homologous ∠s of equal ⊿s).

$\therefore B C$ is ∥ to $A E$,

and $A B$ is ∥ to $E C$, § 69

(when two straight lines lying in the same plane are cut by a third straight line, if the alt.-int. ∠s be equal, the lines are parallel).

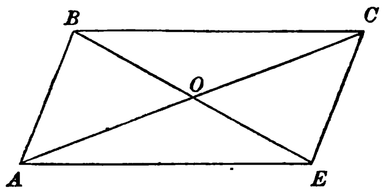
$\therefore$ the figure $A B C E$ is a ▱, § 125

(having its opposite sides parallel).

Q. E. D.

PROPOSITION XLII. THEOREM.

138. *The diagonals of a parallelogram bisect each other.*



Let the figure $ABCE$ be a parallelogram, and let the diagonals AC and BE cut each other at O.

We are to prove $AO = OC$, *and* $BO = OE$.

In the ▵ AOE and BOC

$$AE = BC, \qquad \text{§ 134}$$

(*being opposite sides of a* ▱),

$$\angle OAE = \angle OCB, \qquad \text{§ 68}$$

(*being alt.-int.* ∠s),

$$\angle OEA = \angle OBC; \qquad \text{§ 68}$$

$$\therefore \triangle AOE = \triangle BOC, \qquad \text{§ 107}$$

(*having a side and two adj.* ∠s *of the one equal respectively to a side and two adj.* ∠s *of the other*).

$$\therefore AO = OC,$$

and

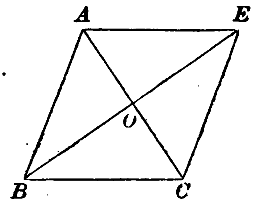
$$BO = OE.$$

(*being homologous sides of equal* ▵).

Q. E. D.

PROPOSITION XLIII. THEOREM.

139. *The diagonals of a rhombus bisect each other at right angles.*



Let the figure $ABCE$ be a rhombus, having the diagonals AC and BE bisecting each other at O.

We are to prove $\angle AOE$ *and* $\angle AOB$ *rt.* $\angle$s.

In the $\triangle$s AOE and AOB,

$AE = AB$, § 128

(being sides of a rhombus);

$OE = OB$, § 138

(the diagonals of a ▱ *bisect each other)*;

$AO = AO$, Iden.

$\therefore \triangle AOE = \triangle AOB$, § 108

(having three sides of the one equal respectively to three sides of the other);

$\therefore \angle AOE = \angle AOB$,

(being homologous $\angle$s *of equal* $\triangle$s*)*;

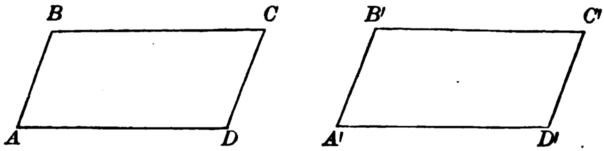
$\therefore \angle AOE$ and $\angle AOB$ are rt. $\angle$s. § 25

(When one straight line meets another straight line so as to make the adj. $\angle$s *equal, each* $\angle$ *is a rt.* $\angle$*).*

Q. E. D.

Proposition XLIV. Theorem.

140. *Two parallelograms, having two sides and the included angle of the one equal respectively to two sides and the included angle of the other, are equal in all respects.*



In the parallelograms $A\,B\,C\,D$ and $A'\,B'\,C'\,D'$, le
$A\,B = A'\,B'$, $A\,D = A'\,D'$, and $\angle\,A = \angle\,A'$.

We are to prove that the ▱s are equal.

Apply ▱ $A\,B\,C\,D$ to ▱ $A'\,B'\,C'\,D'$, so that $A\,D$ will fall on and coincide with $A'\,D'$.

Then $A\,B$ will fall on $A'\,B'$,
(*for* $\angle\,A = \angle\,A'$, *by hyp.*),

and the point B will fall on B',
(*for* $A\,B = A'\,B'$, *by hyp.*).

Now, $B\,C$ and $B'\,C'$ are both ‖ to $A'\,D'$ and are drawn through point B';

$\therefore$ the lines $B\,C$ and $B'\,C'$ coincide, § 66

and C falls on $B'\,C'$ or $B'\,C'$ produced.

In like manner $D\,C$ and $D'\,C'$ are ‖ to $A'\,B'$ and are drawn through the point D'.

$\therefore$ $D\,C$ and $D'\,C'$ coincide; § 66

$\therefore$ the point C falls on $D'\,C'$, or $D'\,C'$ produced;

$\therefore$ C falls on both $B'\,C'$ and $D'\,C'$;

$\therefore$ C must fall on a point common to both, namely, C'.

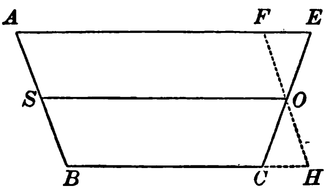
$\therefore$ the two ▱s coincide, and are equal in all respects.

Q. E. D.

141. Corollary. *Two rectangles having the same base and altitude are equal;* for they may be applied to each other and will coincide.

Proposition XLV. Theorem.

142. *The straight line which connects the middle points of the non-parallel sides of a trapezoid is parallel to the parallel sides, and is equal to half their sum.*



Let SO be the straight line joining the middle points of the non-parallel sides of the trapezoid $ABCE$.

We are to prove $SO \parallel$ *to* AE *and* BC;
also $SO = \frac{1}{2}(AE + BC)$.

Through the point O draw $FH \parallel$ to AB,

and produce BC to meet FOH at H.

In the $\triangle$ FOE and COH

$OE = OC$, Cons.

$\angle OEF = \angle OCH$, § 68
(being alt.-int. $\angle$s),

$\angle FOE = \angle COH$, § 49
(being vertical $\angle$s).

$\therefore \triangle FOE = \triangle COH$, § 107
(having a side and two adj. $\angle$s of the one equal respectively to a side and two adj. $\angle$s of the other).

$$\therefore FE = CH,$$

and $$OF = OH,$$
(*being homologous sides of equal* $\triangle$s).

Now $$FH = AB,$$ § 135
(∥ *lines comprehended between* ∥ *lines are equal*);

$$\therefore FO = AS.$$ Ax. 7.

$\therefore$ the figure $AFOS$ is a $\square$, § 136
(*having two opposite sides equal and parallel*).

$\therefore SO$ is ∥ to AF, § 125
(*being opposite sides of a* $\square$).

SO is also ∥ to BC,
(*a straight line* ∥ *to one of two* ∥ *lines is* ∥ *to the other also*).

Now $$SO = AF,$$ § 125
(*being opposite sides of a* $\square$),

and $$SO = BH.$$ § 125

But $$AF = AE - FE,$$

and $$BH = BC + CH.$$

Substitute for AF and BH their equals, $AE - FE$ and $BC + CH$,

and add, observing that $CH = FE$;

then $$2\,SO = AE + BC.$$

$$\therefore SO = \tfrac{1}{2}(AE + BC).$$

Q. E. D.

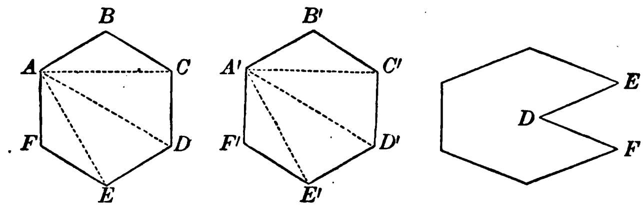
On Polygons in General.

143. Def. A *Polygon* is a plane figure bounded by straight lines.

144. Def. The bounding lines are the *sides* of the polygon, and their sum, as $AB + BC + CD$, etc., is the *Perimeter* of the polygon.

The angles which the adjacent sides make with each other are the angles of the polygon.

145. Def. A *Diagonal* of a polygon is a line joining the vertices of two angles not adjacent.



146. Def. An *Equilateral* polygon is one which has all its sides equal.

147. Def. An *Equiangular* polygon is one which has all its angles equal.

148. Def. A *Convex* polygon is one of which no side, when produced, will enter the surface bounded by the perimeter.

149. Def. Each angle of such a polygon is called a *Salient* angle, and is less than two right angles.

150. Def. A *Concave* polygon is one of which two or more sides, when produced, will enter the surface bounded by the perimeter.

151. Def. The angle FDE is called a *Re-entrant* angle.

When the term polygon is used, a *convex* polygon is meant.

The number of sides of a polygon is evidently equal to the number of its angles.

By drawing diagonals from any vertex of a polygon, the figure may be divided into as many triangles as it has sides less two.

152. Def. Two polygons are *Equal*, when they can be divided by diagonals into the same number of triangles, equal each to each, and similarly placed; for the polygons can be applied to each other, and the corresponding triangles will evidently coincide. Therefore the polygons will coincide, and be equal in all respects.

153. Def. Two polygons are *Mutually Equiangular*, if the angles of the one be equal to the angles of the other, each to each, when taken in the same order; as the polygons $ABCDEF$, and $A'B'C'D'E'F'$, in which $\angle A = \angle A'$, $\angle B = \angle B'$, $\angle C = \angle C'$, etc.

154. Def. The equal angles in mutually equiangular polygons are called *Homologous* angles; and the sides which lie *between* equal angles are called *Homologous* sides.

155. Def. Two polygons are *Mutually Equilateral*, if the sides of the one be equal to the sides of the other, each to each, when taken in the same order.

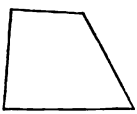


Fig. 1.


Fig. 2.

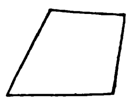


Fig. 3.

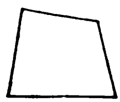


Fig. 4.

Two polygons may be mutually equiangular without being mutually equilateral; as Figs. 1 and 2.

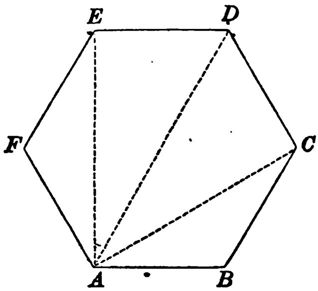
And, *except in the case of triangles*, two polygons may be mutually equilateral without being mutually equiangular; as Figs. 3 and 4.

If two polygons be mutually equilateral and equiangular, *they are equal*, for they may be applied the one to the other so as to coincide.

156. Def. A polygon of three sides is a *Trigon* or *Triangle;* one of four sides is a *Tetragon* or *Quadrilateral;* one of five sides is a *Pentagon;* one of six sides is a *Hexagon;* one of seven sides is a *Heptagon;* one of eight sides is an *Octagon;* one of ten sides is a *Decagon;* one of twelve sides is a *Dodecagon.*

Proposition XLVI. Theorem.

157. *The sum of the interior angles of a polygon is equal to two right angles, taken as many times less two as the figure has sides.*



Let the figure ABCDEF be a polygon having n sides.

We are to prove

$$\angle A + \angle B + \angle C, \text{ etc.}, = 2 \text{ rt. } \angle s\ (n - 2).$$

From the vertex A draw the diagonals AC, AD, and AE.

The sum of the $\angle s$ of the $\triangle s$ = the sum of the angles of the polygon.

Now there are $(n - 2)$ $\triangle s$,

and the sum of the $\angle s$ of each $\triangle = 2$ rt. $\angle s$. § 98

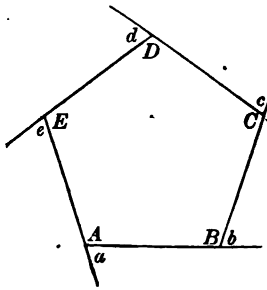
$\therefore$ the sum of the $\angle s$ of the $\triangle s$, that is, the sum of the $\angle s$ of the polygon $= 2$ rt. $\angle s\ (n - 2)$.

Q. E. D.

158. Corollary. The sum of the angles of a quadrilateral equals two right angles taken $(4 - 2)$ times, i. e. equals 4 right angles; and if the angles be all equal, each angle is a right angle. In general, each angle of an equiangular polygon of n sides is equal to $\frac{2(n-2)}{n}$ right angles.

Proposition XLVII. Theorem.

159. *The exterior angles of a polygon, made by producing each of its sides in succession, are together equal to four right angles.*



Let the figure ABCDE be a polygon, having its sides produced in succession.

We are to prove the sum of the ext. $\angle$s $= 4$ *rt.* $\angle$s.

Denote the int. $\angle$s of the polygon by A, B, C, D, E;

and the ext. $\angle$s by a, b, c, d, e.

$$\angle A + \angle a = 2 \text{ rt. } \angle\text{s}, \qquad \S\ 34$$

(*being sup.-adj.* $\angle$s).

$$\angle B + \angle b = 2 \text{ rt. } \angle\text{s}. \qquad \S\ 34$$

In like manner each pair of adj. $\angle$s $= 2$ rt. $\angle$s;

$\therefore$ the sum of the interior and exterior $\angle$s $= 2$ rt. $\angle$s taken as many times as the figure has sides,

or, $\quad 2\,n$ rt. $\angle$s.

But the interior $\angle$s $= 2$ rt. $\angle$s taken as many times as the figure has sides less two, $= 2$ rt. $\angle$s $(n - 2)$,

or, $\quad 2\,n$ rt. $\angle$s $- 4$ rt. $\angle$s.

$\therefore$ the exterior $\angle$s $= 4$ rt. $\angle$s.

Q. E. D.

Exercises.

1. Show that the sum of the interior angles of a hexagon is equal to eight right angles.

2. Show that each angle of an equiangular pentagon is $\frac{6}{5}$ of a right angle.

3. How many sides has an equiangular polygon, four of whose angles are together equal to seven right angles?

4. How many sides has the polygon the sum of whose interior angles is equal to the sum of its exterior angles?

5. How many sides has the polygon the sum of whose interior angles is double that of its exterior angles?

6. How many sides has the polygon the sum of whose exterior angles is double that of its interior angles?

7. Every point in the bisector of an angle is equally distant from the sides of the angle; and every point not in the bisector, but within the angle, is unequally distant from the sides of the angle.

8. BAC is a triangle having the angle B double the angle A. If BD bisect the angle B, and meet AC in D, show that BD is equal to AD.

9. If a straight line drawn parallel to the base of a triangle bisect one of the sides, show that it bisects the other also; and that the portion of it intercepted between the two sides is equal to one half the base.

10. $ABCD$ is a parallelogram, E and F the middle points of AD and BC respectively; show that BE and DF will trisect the diagonal AC.

11. If from any point in the base of an isosceles triangle parallels to the equal sides be drawn, show that a parallelogram is formed whose perimeter is equal to the sum of the equal sides of the triangle.

12. If from the diagonal BD of a square $ABCD$, BE be cut off equal to BC, and EF be drawn perpendicular to BD, show that DE is equal to EF, and also to FC.

13. Show that the three lines drawn from the vertices of a triangle to the middle points of the opposite sides meet in a point.

BOOK II.

CIRCLES.

DEFINITIONS.

160. DEF. A *Circle* is a plane figure bounded by a curved line, all the points of which are equally distant from a point within called the *Centre.*

161. DEF. The *Circumference* of a circle is the line which bounds the circle.

162. DEF. A *Radius* of a circle is any straight line drawn from the centre to the circumference, as $O\,A$, Fig. 1.

163. DEF. A *Diameter* of a circle is any straight line passing through the centre and having its extremities in the circumference, as $A\,B$, Fig. 2.

By the definition of a circle, all its radii are equal. Hence, all its diameters are equal, since the diameter is equal to twice the radius.

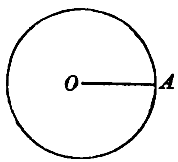


Fig. 1.

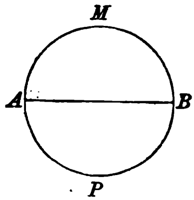


Fig. 2.

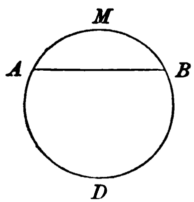


Fig. 3.

164. DEF. An *Arc* of a circle is any portion of the circumference, as $A\,M\,B$, Fig. 3.

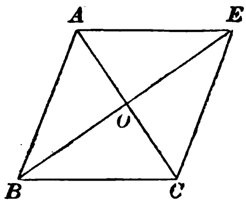
165. DEF. A *Semi-circumference* is an arc equal to one half the circumference, as $A\,M\,B$, Fig. 2.

166. DEF. A *Chord* of a circle is any straight line having its extremities in the circumference, as $A\,B$, Fig. 3.

Every chord subtends two arcs whose sum is the circumference. Thus the chord $A\,B$, (Fig. 3), subtends the arc $A\,M\,B$ and the arc $A\,D\,B$. Whenever a chord and its arc are spoken of, the less arc is meant unless it be otherwise stated.

PROPOSITION XLIII. THEOREM.

139. ***The diagonals of a rhombus bisect each other at right angles.***



Let the figure $ABCE$ be a rhombus, having the diagonals AC and BE bisecting each other at O.

We are to prove $\angle AOE$ *and* $\angle AOB$ *rt.* $\angle$s.

In the $\triangle$s AOE and AOB,

$$AE = AB, \qquad \text{§ 128}$$
(being sides of a rhombus);

$$OE = OB, \qquad \text{§ 138}$$
(the diagonals of a $\square$ *bisect each other)*;

$$AO = AO, \qquad \text{Iden.}$$

$$\therefore \triangle AOE = \triangle AOB, \qquad \text{§ 108}$$
(having three sides of the one equal respectively to three sides of the other);

$$\therefore \angle AOE = \angle AOB,$$
(being homologous $\angle$s *of equal* $\triangle$s*)*;

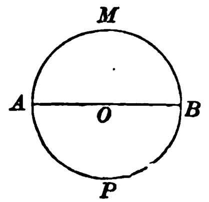
$$\therefore \angle AOE \text{ and } \angle AOB \text{ are rt. } \angle\text{s}. \qquad \text{§ 25}$$

(When one straight line meets another straight line so as to make the adj. $\angle$s *equal, each* $\angle$ *is a rt.* $\angle$*).*

Q. E. D.

175. Def. *Equal circles* are circles which have equal radii. For if one circle be applied to the other so that their centres coincide their circumferences will coincide, since all the points of both are at the same distance from the centre.

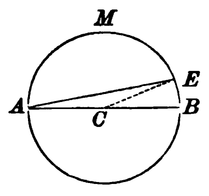
176. *Every diameter bisects the circle and its circumference.* For if we fold over the segment $A\,M\,B$ on $A\,B$ as an axis until it comes into the plane of $A\,P\,B$, the arc $A\,M\,B$ will coincide with the arc $A\,P\,B$; because every point in each is equally distant from the centre O.



Proposition I. Theorem.

177. *The diameter of a circle is greater than any other chord.*

Let $A\,B$ be the diameter of the circle $A\,M\,B$, and $A\,E$ any other chord.



We are to prove $A\,B > A\,E$.

From C, the centre of the ⊙, draw $C\,E$.

$$C\,E = C\,B,$$

(being radii of the same circle).

But $$A\,C + C\,E > A\,E, \qquad \S\ 96$$

(the sum of two sides of a △ > the third side).

Substitute for $C\,E$, in the above inequality, its equal $C\,B$.

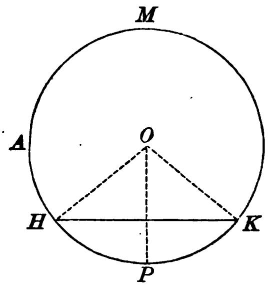
Then $$A\,C + C\,B > A\,E, \text{ or}$$

$$A\,B > A\,E.$$

Q. E. D.

PROPOSITION II. THEOREM.

178. ***A straight line cannot intersect the circumference of a circle in more than two points.***



Let HK be any line cutting the circumference AMP.

We are to prove that HK can intersect the circumference in only two points.

If it be possible, let HK intersect the circumference in three points, H, P, and K.

From O, the centre of the ⊙, draw the radii OH, OP, and OK.

Then OH, QP, and OK are equal, § 163
(being radii of the same circle).

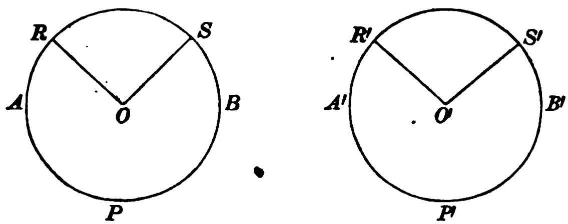
∴ if HK could intersect the circumference in three points, we should have three equal straight lines OH, OP, and OK drawn from the same point to a given straight line, which is impossible, § 56
(only two equal straight lines can be drawn from a point to a straight line).

∴ a straight line can intersect the circumference in only two points.

Q. E. D.

PROPOSITION III. THEOREM.

179. *In the same circle, or equal circles, equal angles at the centre intercept equal arcs on the circumference.*



In the equal circles ABP and $A'B'P'$ let $\angle O = \angle O'$.

We are to prove arc RS = arc $R'S'$.

Apply $\odot ABP$ to $\odot A'B'P'$,

so that $\angle O$ shall coincide with $\angle O'$.

The point R will fall upon R', § 176
(for $OR = O'R'$, being radii of equal ⑤),

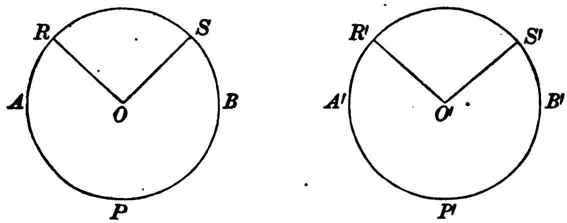
and the point S will fall upon S', § 176
(for $OS = O'S'$, being radii of equal ⑤).

Then the arc RS must coincide with the arc $R'S'$. For, otherwise, there would be some points in the circumference unequally distant from the centre, which is contrary to the definition of a circle. § 160

Q. E. D.

Proposition IV. Theorem.

180. Conversely: *In the same circle, or equal circles, equal arcs subtend equal angles at the centre.*



In the equal circles ABP and $A'B'P'$ let arc RS = arc $R'S'$.

We are to prove $\angle ROS = \angle R'O'S'$.

Apply $\odot ABP$ to $\odot A'B'P'$,

so that the radius OR shall fall upon $O'R'$.

Then S, the extremity of arc RS,

will fall upon S', the extremity of arc $R'S'$,
(*for* $RS = R'S'$, *by hyp.*).

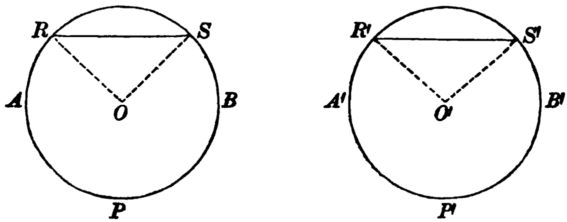
$\therefore OS$ will coincide with $O'S'$, § 18
(*their extremities being the same points*).

$\therefore \angle ROS$ will coincide with, and be equal to, $\angle R'O'S'$.

Q. E. D.

PROPOSITION V. THEOREM.

181. *In the same circle, or equal circles, equal arcs are subtended by equal chords.*



In the equal circles ABP and $A'B'P'$ let arc RS = arc $R'S'$.

We are to prove chord RS = chord $R'S'$.

Draw the radii OR, OS, $O'R'$, and $O'S'$.

In the $\triangle\triangle$ ROS and $R'O'S'$

$$OR = O'R', \qquad \S\ 176$$

(being radii of equal ⊙s),

$$OS = O'S', \qquad \S\ 176$$

$$\angle O = \angle O', \qquad \S\ 180$$

(equal arcs in equal ⊙s subtend equal ∠s at the centre).

$$\therefore \triangle ROS = \triangle R'O'S', \qquad \S\ 106$$

(two sides and the included ∠ of the one being equal respectively to two sides and the included ∠ of the other).

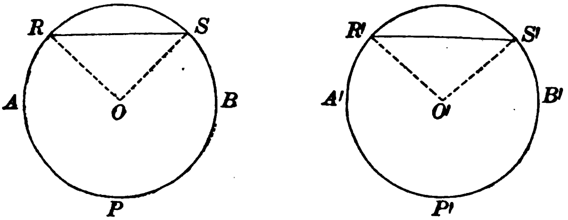
$\therefore$ chord RS = chord $R'S'$,

(being homologous sides of equal $\triangle\triangle$).

Q. E. D.

PROPOSITION VI. THEOREM.

182. CONVERSELY: *In the same circle, or equal circles, equal chords subtend equal arcs.*



In the equal circles ABP and $A'B'P'$, let chord RS = chord $R'S'$.

We are to prove arc RS = arc $R'S'$.

Draw the radii OR, OS, $O'R'$, and $O'S'$.

In the $\triangle$ ROS and $R'O'S'$

$RS = R'S'$, Hyp.

$OR = O'R'$, § 176

(being radii of equal ⊙s),

$OS = O'S'$; § 176

$\therefore \triangle ROS = \triangle R'O'S'$, § 108

(three sides of the one being equal to three sides of the other).

$\therefore \angle O = \angle O'$,

(being homologous $\angle$s of equal $\triangle$s).

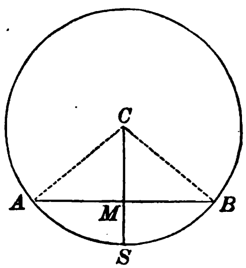
$\therefore$ arc RS = arc $R'S'$, § 179

(in the same ⊙, or equal ⊙s, equal $\angle$s at the centre intercept equal arcs on the circumference).

Q. E. D.

Proposition VII. Theorem.

183. *The radius perpendicular to a chord bisects the chord and the arc subtended by it.*



Let AB be the chord, and let the radius CS be perpendicular to AB at the point M.

We are to prove $AM = BM$, *and arc* $AS =$ *arc* BS.

Draw CA and CB.

$CA = CB$,

(being radii of the same ⊙);

$\therefore \triangle ACB$ is isosceles, § 84

(the opposite sides being equal);

$\therefore \perp CS$ bisects the base AB and the $\angle C$, § 113

(the $\perp$ drawn from the vertex to the base of an isosceles $\triangle$ bisects the base and the $\angle$ at the vertex).

$\therefore AM = BM$.

Also, since $\angle ACS = \angle BCS$,

arc $AS =$ arc SB, § 179

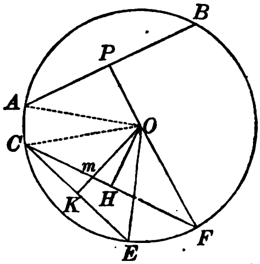
(equal $\angle$s at the centre intercept equal arcs on the circumference).

Q. E. D.

184. Corollary. The perpendicular erected at the middle of a chord passes through the centre of the circle, and bisects the arc of the chord.

PROPOSITION VIII. THEOREM.

185. *In the same circle, or equal circles, equal chords are equally distant from the centre; and of two unequal chords the less is at the greater distance from the centre.*



In the circle $ABEC$ let the chord AB equal the chord CF, and the chord CE be less than the chord CF. Let OP, OH, and OK be $\perp$s drawn to these chords from the centre O.

We are to prove $OP = OH$, *and* $OH < OK$.

Join OA and OC.

In the rt. $\triangle$s AOP and COH

$OA = OC$,
(being radii of the same ⊙*)*;

$AP = CH$, § 183
(being halves of equal chords);

$\therefore \triangle AOP = \triangle COH$. § 109

$\therefore OP = OH$.

Again, since $CE < CF$,

the $\angle COE < COF$, § 116

and the arc $CE <$ the arc CF.

$\therefore \perp OK$ will intersect CF in some point, as m.

Now $OK > Om$. Ax. 8

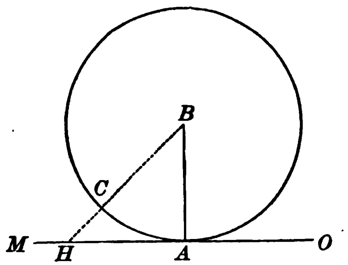
But $Om > OH$, § 52
(a $\perp$ is the shortest distance from a point to a straight line).

$\therefore$ much more is $OK > OH$.

Q. E. D.

PROPOSITION IX. THEOREM.

186. *A straight line perpendicular to a radius at its extremity is a tangent to the circle.*



Let BA be the radius, and MO the straight line perpendicular to BA at A.

We are to prove MO *tangent to the circle.*

From B draw any other line to MO, as BCH.

$BH > BA$, § 52

(*a* $\perp$ *measures the shortest distance from a point to a straight line*).

$\therefore$ point H is without the circumference.

But BH is any other line than BA,

$\therefore$ *every* point of the line MO is without the circumference, except A.

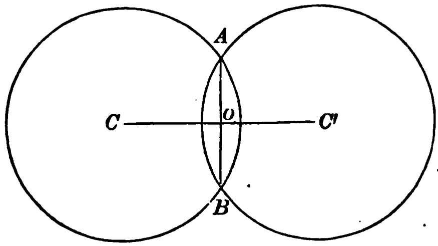
$\therefore$ MO is a tangent to the circle at A. § 171

Q. E. D.

187. COROLLARY. When a straight line is tangent to a circle, it is perpendicular to the radius drawn to the point of contact, and therefore a perpendicular to a tangent at the point of contact passes through the centre of the circle.

PROPOSITION X. THEOREM.

188. *When two circumferences intersect each other, the line which joins their centres is perpendicular to their common chord at its middle point.*



Let C and C' be the centres of two circumferences which intersect at A and B. Let AB be their common chord, and CC' join their centres.

We are to prove CC' ⊥ to AB at its middle point.

A ⊥ drawn through the middle of the chord AB passes through the centres C and C', § 184

(*a ⊥ erected at the middle of a chord passes through the centre of the ⊙*).

∴ the line CC', having two points in common with this ⊥, must coincide with it.

∴ CC' is ⊥ to AB at its middle point.

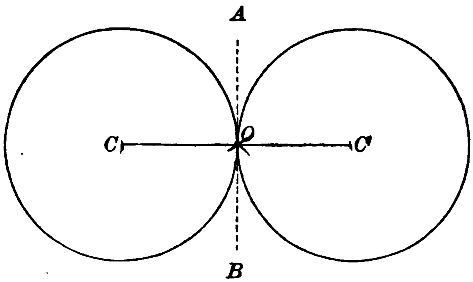
Q. E. D.

Ex. 1. Show that, of all straight lines drawn from a point without a circle to the circumference, the least is that which, when produced, passes through the centre.

Ex. 2. Show that, of all straight lines drawn from a point within or without a circle to the circumference, the greatest is that which meets the circumference after passing through the centre.

PROPOSITION XI. THEOREM.

189. *When two circumferences are tangent to each other their point of contact is in the straight line joining their centres.*



Let the two circumferences, whose centres are C and C′, touch each other at O, in the straight line A B, and let C C′ be the straight line joining their centres.

We are to prove O *is in the straight line* $C\,C'$.

A $\perp$ to $A\,B$, drawn through the point O, passes through the centres C and C', § 187

(*a* $\perp$ *to a tangent at the point of contact passes through the centre of the* $\odot$).

$\therefore$ the line $C\,C'$, having two points in common with this $\perp$, must coincide with it.

$\therefore$ O is in the straight line $C\,C'$.

Q. E. D.

Ex. $A\,B$, a chord of a circle, is the base of an isosceles triangle whose vertex C is without the circle, and whose equal sides meet the circle in D and E. Show that $C\,D$ is equal to $C\,E$.

On Measurement.

190. Def. To *measure* a quantity of any kind is to find how *many times* it contains another known quantity of the *same kind.* Thus, to measure a line is to find how many times it contains another known line, called the *linear unit.*

191. Def. The number which expresses how many times a quantity contains the unit, prefixed to the name of the unit, is called the *numerical measure* of that quantity; as 5 yards, etc.

192. Def. Two quantities are *commensurable* if there be some third quantity of the same kind which is contained an exact number of times in each. This third quantity is called the *common measure* of these quantities, and each of the given quantities is called a *multiple* of this common measure.

193. Def. Two quantities are *incommensurable* if they have no common measure.

194. Def. The magnitude of a quantity is always *relative* to the magnitude of another quantity of the *same kind.* No quantity is great or small except by comparison. This relative magnitude is called their *Ratio,* and this ratio is always an *abstract number.*

When two quantities of the same kind are measured by the *same unit,* their ratio is the ratio of their *numerical measures.*

195. The ratio of a to b is written $\frac{a}{b}$, or $a : b$, and by this is meant:

How many times b is contained in a; a————
or, what part a is of b. b——

I. If b be contained an exact number of times in a their ratio is a *whole number.*

If b be not contained an exact number of times in a, but if there be a common measure which is contained m times in a and n times in b, their ratio is the *fraction* $\frac{m}{n}$.

II. If a and b be incommensurable, their ratio cannot be exactly expressed in figures. But if b be divided into n equal parts, and one of these parts be contained m times in a with a remainder less than $\frac{1}{n}$ part of b, then $\frac{m}{n}$ is an *approximate value* of the ratio $\frac{a}{b}$, correct within $\frac{1}{n}$.

Again, if each of these equal parts of b be divided into n equal parts; that is, if b be divided into n^2 equal parts, and if one of these parts be contained m' times in a with a remainder less than $\frac{1}{n^2}$ part of b, then $\frac{m'}{n^2}$ is a *nearer approximate value* of the ratio $\frac{a}{b}$, correct within $\frac{1}{n^2}$.

By continuing this process, a series of variable values, $\frac{m}{n}$, $\frac{m'}{n^2}$, $\frac{m''}{n^3}$, etc., will be obtained, which will differ less and less from the exact value of $\frac{a}{b}$. We may thus find a fraction which shall differ from this exact value by as little as we please, that is, by less than any assigned quantity.

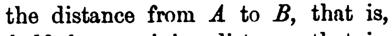
Hence, an *incommensurable ratio* is the *limit* toward which its successive approximate values are constantly tending.

On the Theory of Limits.

196. Def. When a quantity is regarded as having a *fixed* value, it is called a *Constant;* but, when it is regarded, under the conditions imposed upon it, as having an *indefinite number* of *different* values, it is called a *Variable.*

197. Def. When it can be shown that the value of a variable, measured at a series of definite intervals, can by indefinite continuation of the series be made to differ from a given constant by less than any assigned quantity, however small, but cannot be made absolutely equal to the constant, that constant is called the *Limit* of the variable, and the variable is said to *approach indefinitely to its limit.*

If the variable be increasing, its limit is called a *superior* limit; if decreasing, an *inferior* limit.

198. Suppose a point 

to move from A toward B, under the conditions that the first second it shall move one-half the distance from A to B, that is, to M; the next second, one-half the remaining distance, that is, to M'; the next second, one-half the remaining distance, that is, to M'', and so on indefinitely.

Then it is evident that the moving point *may approach as near to B as we please, but will never arrive at B.* For, however

near it may be to B at any instant, the next second it will pass over one-half the interval still remaining; it must, therefore, approach nearer to B, since *half* the interval still remaining is *some* distance, but will not reach B, since *half* the interval still remaining is not the *whole* distance.

Hence, the distance from A to the moving point is an increasing variable, which indefinitely approaches the constant AB as its *limit;* and the distance from the moving point to B is a decreasing variable, which indefinitely approaches the constant zero as its *limit.*

If the length of AB be two inches, and the variable be denoted by x, and the difference between the variable and its limit, by v:

after one second,	$x = 1,$	$v = 1;$
after two seconds,	$x = 1 + \frac{1}{2},$	$v = \frac{1}{2};$
after three seconds,	$x = 1 + \frac{1}{2} + \frac{1}{4},$	$v = \frac{1}{4};$
after four seconds,	$x = 1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8},$	$v = \frac{1}{8};$

and so on indefinitely.

Now the sum of the series $1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8}$ etc., is evidently less than 2; but by taking a great number of terms, the sum can be made to differ from 2 by as little as we please. Hence 2 is the limit of the sum of the series, when the number of the terms is increased indefinitely; and 0 is the limit of the variable difference between this variable sum and 2.

lim. will be used as an abbreviation for limit.

199. [1] *The difference between a variable and its limit is a variable whose limit is zero.*

[2] *If two or more variables, v, v', v'', etc., have zero for a limit, their sum, $v + v' + v''$, etc., will have zero for a limit.*

[3] *If the limit of a variable, v, be zero, the limit of $a \pm v$ will be the constant a, and the limit of $a \times v$ will be zero.*

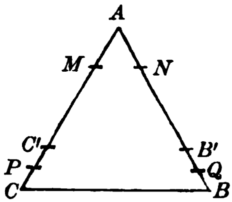
[4] *The product of a constant and a variable is also a variable, and the limit of the product of a constant and a variable is the product of the constant and the limit of the variable.*

[5] *The sum or product of two variables, both of which are either increasing or decreasing, is also a variable.*

Proposition I.

[6] *If two variables be always equal, their limits are equal.*

Let the two variables AM and AN be always equal, and let AC and AB be their respective limits.



We are to prove $AC = AB$.

Suppose $AC > AB$. Then we may diminish AC to some value AC' such that $AC' = AB$.

Since AM approaches indefinitely to AC, we may suppose that it has reached a value AP greater than AC'.

Let AQ be the corresponding value of AN.

Then $AP = AQ$.

Now $AC' = AB$.

But both of these equations cannot be true, for $AP > AC'$, and $AQ < AB$. $\therefore AC$ cannot be greater than AB.

Again, suppose $AC < AB$. Then we may diminish AB to some value AB' such that $AC = AB'$.

Since AN approaches indefinitely to AB we may suppose that it has reached a value AQ greater than AB'.

Let AP be the corresponding value of AM.

Then $AP = AQ$.

Now $AC = AB'$.

But both of these equations cannot be true, for $AP < AC$, and $AQ > AB'$. $\therefore AC$ cannot be less than AB.

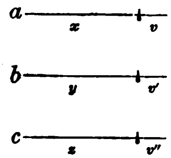
Since AC cannot be greater or less than AB, it must be equal to AB. Q. E. D.

[7] Corollary 1. *If two variables be in a constant ratio, their limits are in the same ratio.* For, let x and y be two variables having the constant ratio r, then $\frac{x}{y} = r$, or, $x = ry$, therefore $lim.\ (x) = lim.\ (ry) = r \times lim.\ (y)$, therefore $\frac{lim.\ (x)}{lim.\ (y)} = r$.

[8] Cor. 2. Since an incommensurable ratio is the limit of its successive approximate values, *two incommensurable ratios $\frac{a}{b}$ and $\frac{a'}{b'}$ are equal if they always have the same approximate values when expressed within the same measure of precision.*

PROPOSITION II.

[9] *The limit of the algebraic sum of two or more variables is the algebraic sum of their limits.*



Let x, y, z, ***be variables,*** a, b, ***and*** c, ***their respective limits, and*** v, v', ***and*** v'', ***the variable differences between*** x, y, z, ***and*** a, b, c, ***respectively.***

We are to prove $lim. (x + y + z) = a + b + c.$

Now, $x = a - v,\ y = b - v',\ z = c - v''.$

Then, $x + y + z = a - v + b - v' + c - v''.$

$\therefore lim. (x + y + z) = lim. (a - v + b - v' + c - v'').$ [6]

But, $lim. (a - v + b - v' + c - v'') = a + b + c.$ [3]

$\therefore lim. (x + y + z) = a + b + c.$

Q. E. D.

PROPOSITION III.

[10] *The limit of the product of two or more variables is the product of their limits.*

Let x, y, z, ***be variables,*** a, b, c, ***their respective limits, and*** v, v', v'', ***the variable differences between*** x, y, z, ***and*** a, b, c, ***respectively.***

We are to prove $lim. (x\,y\,z) = a\,b\,c.$

Now, $x = a - v,\ y = b - v',\ z = c - v''.$

Multiply these equations together.

Then, $x\,y\,z = a\,b\,c \mp$ terms which contain one or more of the factors v, v', v'', and hence have zero for a limit. [3]

$\therefore lim. (x\,y\,z) = lim. (a\,b\,c \mp$ terms whose limits are zero). [6]

But $lim. (a\,b\,c \mp$ terms whose limits are zero) $= a\,b\,c.$

$\therefore lim. (x\,y\,z) = a\,b\,c.$

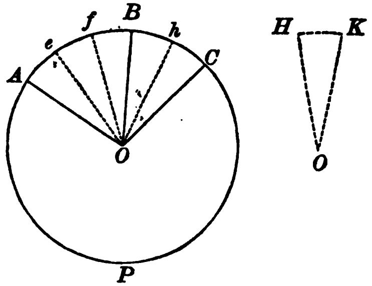
Q. E. D.

For *decreasing* variables the proofs are similar.

NOTE. — In the application of the principles of limits, reference to this section (§ 199) will always include the *fundamental truth* of limits contained in Proposition I.; and it will be left as an exercise for the student to determine in each case what other truths of this section, if any, are included in the reference.

Proposition XII. Theorem.

200. *In the same circle, or equal circles, two commensurable arcs have the same ratio as the angles which they subtend at the centre.*



In the circle APC let the two arcs be AB and AC, and AOB and AOC the $\angle$s which they subtend.

We are to prove $\dfrac{\text{arc } AB}{\text{arc } AC} = \dfrac{\angle AOB}{\angle AOC}$.

Let HK be a common measure of AB and AC.

Suppose HK to be contained in AB three times, and in AC five times.

Then $$\frac{\text{arc } AB}{\text{arc } AC} = \frac{3}{5}.$$

At the several points of division on AB and AC draw radii.

These radii will divide $\angle AOC$ into five equal parts, of which $\angle AOB$ will contain three, § 180
(in the same ⊙, or equal ⊙s, equal arcs subtend equal $\angle$s at the centre).

$$\therefore \frac{\angle AOB}{\angle AOC} = \frac{3}{5}.$$

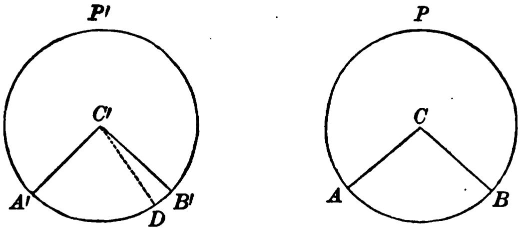
But $$\frac{\text{arc } AB}{\text{arc } AC} = \frac{3}{5}.$$

$$\therefore \frac{\text{arc } AB}{\text{arc } AC} = \frac{\angle AOB}{\angle AOC}.$$ Ax. 1.

Q. E. D.

PROPOSITION XIII. THEOREM.

201. *In the same circle, or in equal circles, incommensurable arcs have the same ratio as the angles which they subtend at the centre.*



In the two equal ⊙ ABP and $A'B'P'$ let AB and $A'B'$ be two incommensurable arcs, and C, C' the ∠s which they subtend at the centre.

We are to prove $\frac{\text{arc } A'B'}{\text{arc } AB} = \frac{\angle C'}{\angle C}$.

Let AB be divided into any number of equal parts, and let one of these parts be applied to $A'B'$ as often as it will be contained in $A'B'$.

Since AB and $A'B'$ are incommensurable, a certain number of these parts will extend from A' to some point, as D, leaving a remainder DB' less than one of these parts.

Draw $C'D$.

Since AB and $A'D$ are commensurable,

$$\frac{\text{arc } A'D}{\text{arc } AB} = \frac{\angle A'C'D}{\angle ACB}, \qquad \text{§ 200}$$

(two commensurable arcs have the same ratio as the ∠s which they subtend at the centre).

Now suppose the number of parts into which AB is divided to be continually increased; then the length of each part will become less and less, and the point D will approach nearer and nearer to B', that is, the arc $A'D$ will approach the arc $A'B'$ as its limit, and the $\angle A'C'D$ the $\angle A'C'B'$ as its limit.

Then the limit of $\frac{\text{arc } A'D}{\text{arc } AB}$ will be $\frac{\text{arc } A'B'}{\text{arc } AB}$,

and the limit of $\frac{\angle A'C'D}{\angle ACB}$ will be $\frac{\angle A'C'B'}{\angle ACB}$.

Moreover, the corresponding values of the two variables, namely,

$$\frac{\text{arc } A'D}{\text{arc } AB} \text{ and } \frac{\angle A'C'D}{\angle ACB},$$

are equal, however near these variables approach their limits.

$\therefore$ their limits $\frac{\text{arc } A'B'}{\text{arc } AB}$ and $\frac{\angle A'C'B'}{\angle ACB}$ are equal. § 199

Q. E. D.

202. Scholium. *An angle at the centre is said to be measured by its intercepted arc.* This expression means that an angle at the centre is such part of the angular magnitude about that point (four right angles) as its intercepted arc is of the whole circumference.

A circumference is divided into 360 equal arcs, and each arc is called a degree, denoted by the symbol (°).

The angle at the centre which one of these equal arcs subtends is also called a degree.

A quadrant (one-fourth a circumference) contains therefore 90°; and a right angle, subtended by a quadrant, contains 90°.

Hence an angle of 30° is $\frac{1}{3}$ of a right angle, an angle of 45° is $\frac{1}{2}$ of a right angle, an angle of 135° is $\frac{3}{2}$ of a right angle.

Thus we get a definite idea of an angle if we know the number of degrees it contains.

A degree is subdivided into sixty equal parts called minutes, denoted by the symbol (′).

A minute is subdivided into sixty equal parts called seconds, denoted by the symbol (″).

PROPOSITION XIV. THEOREM.

203. *An inscribed angle is measured by one-half of the arc intercepted between its sides.*

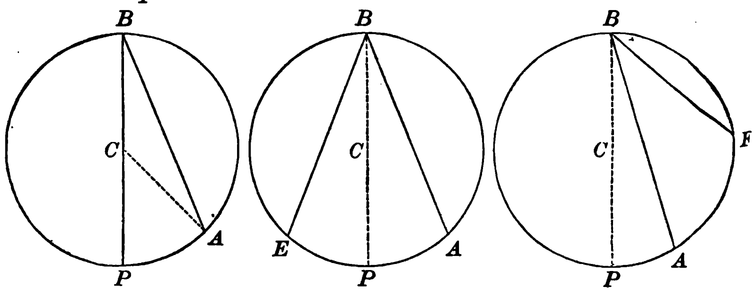


Fig. 1. Fig. 2. Fig. 3.

CASE I.

In the circle PAB (Fig. 1), let the centre C be in one of the sides of the inscribed angle B.

We are to prove $\angle B$ *is measured by* $\frac{1}{2}$ *arc* PA.

Draw CA.

$$CA = CB,$$

(*being radii of the same* ⊙).

$$\therefore \angle B = \angle A, \qquad \S\ 112$$

(*being opposite equal sides*).

$$\angle PCA = \angle B + \angle A. \qquad \S\ 105$$

(*the exterior* $\angle$ *of a* $\triangle$ *is equal to the sum of the two opposite interior* $\angle$*s*).

Substitute in the above equality $\angle B$ for its equal $\angle A$.

Then we have $\angle PCA = 2 \angle B$.

But $\angle PCA$ is measured by AP, § 202

(*the* $\angle$ *at the centre is measured by the intercepted arc*).

$\therefore 2 \angle B$ is measured by AP.

$\therefore \angle B$ is measured by $\frac{1}{2} AP$.

CASE II.

In the circle BAE (Fig. 2), let the centre C fall within the angle EBA.

We are to prove $\angle EBA$ *is measured by* $\frac{1}{2}$ *arc* EA.

Draw the diameter BCP.

$\angle PBA$ is measured by $\frac{1}{2}$ arc PA, (Case I.)

$\angle PBE$ is measured by $\frac{1}{2}$ arc PE, (Case I.)

$\therefore \angle PBA + \angle PBE$ is measured by $\frac{1}{2}$ (arc PA + arc PE).

$\therefore \angle EBA$ is measured by $\frac{1}{2}$ arc EA.

CASE III.

In the circle BFP (Fig. 3), let the centre C fall without the angle ABF.

We are to prove $\angle ABF$ *is measured by* $\frac{1}{2}$ *arc* AF.

Draw the diameter BCP.

$\angle PBF$ is measured by $\frac{1}{2}$ arc PF, (Case I.)

$\angle PBA$ is measured by $\frac{1}{2}$ arc PA, (Case I.)

$\therefore \angle PBF - \angle PBA$ is measured by $\frac{1}{2}$ (arc PF − arc PA).

$\therefore \angle ABF$ is measured by $\frac{1}{2}$ arc AF.

Q. E. D.

204. COROLLARY 1. An angle inscribed in a semicircle is a right angle, for it is measured by one-half a semi-circumference, or by 90°.

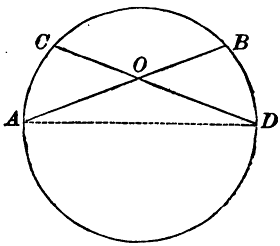
205. COR. 2. An angle inscribed in a segment greater than a semicircle is an acute angle; for it is measured by an arc less than one-half a semi-circumference; i. e. by an arc less than 90°.

206. COR. 3. An angle inscribed in a segment less than a semicircle is an obtuse angle, for it is measured by an arc greater than one-half a semi-circumference; i. e. by an arc greater than 90°.

207. COR. 4. All angles inscribed in the same segment are equal, for they are measured by one-half the same arc.

Proposition XV. Theorem.

208. *An angle formed by two chords, and whose vertex lies between the centre and the circumference, is measured by one-half the intercepted arc plus one-half the arc intercepted by its sides produced.*



Let the $\angle AOC$ be formed by the chords AB and CD.

We are to prove

$\angle AOC$ *is measured by* $\frac{1}{2}$ *arc* $AC + \frac{1}{2}$ *arc* BD.

Draw AD.

$$\angle COA = \angle D + \angle A, \qquad \S\ 105$$

(*the exterior $\angle$ of a $\triangle$ is equal to the sum of the two opposite interior $\angle$s*).

But $\angle D$ is measured by $\frac{1}{2}$ arc AC, § 203

(*an inscribed $\angle$ is measured by $\frac{1}{2}$ the intercepted arc*);

and $\angle A$ is measured by $\frac{1}{2}$ arc BD, § 203

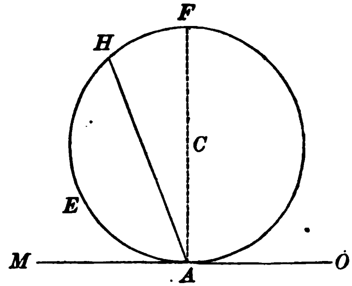
$\therefore \angle COA$ is measured by $\frac{1}{2}$ arc $AC + \frac{1}{2}$ arc BD.

Q. E. D.

Ex. Show that the least chord that can be drawn through a given point in a circle is perpendicular to the diameter drawn through the point.

PROPOSITION XVI. THEOREM.

209. *An angle formed by a tangent and a chord is measured by one-half the intercepted arc.*



Let HAM be the angle formed by the tangent OM and chord AH.

We are to prove

$\angle HAM$ *is measured by* $\frac{1}{2}$ *arc* AEH.

Draw the diameter ACF.

$\angle FAM$ is a rt. $\angle$, § 186

(*the radius drawn to a tangent at the point of contact is* $\perp$ *to it*).

$\angle FAM$, being a rt. $\angle$, is measured by $\frac{1}{2}$ the semi-circumference AEF.

$\angle FAH$ is measured by $\frac{1}{2}$ arc FH, § 203

(*an inscribed* $\angle$ *is measured by* $\frac{1}{2}$ *the intercepted arc*);

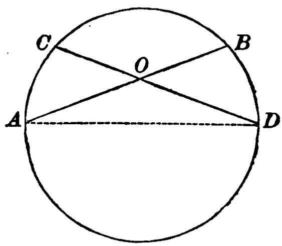
$\therefore \angle FAM - \angle FAH$ is measured by $\frac{1}{2}$ (arc AEF — arc HF).

$\therefore \angle HAM$ is measured by $\frac{1}{2}$ arc AEH.

Q. E. D.

PROPOSITION XV. THEOREM.

208. *An angle formed by two chords, and whose vertex lies between the centre and the circumference, is measured by one-half the intercepted arc plus one-half the arc intercepted by its sides produced.*



Let the $\angle A O C$ be formed by the chords $A B$ and $C D$.

We are to prove

$\angle A O C$ *is measured by* $\frac{1}{2}$ *arc* $A C + \frac{1}{2}$ *arc* $B D$.

Draw $A D$.

$\angle C O A = \angle D + \angle A$, § 105

(the exterior $\angle$ of a $\triangle$ is equal to the sum of the two opposite interior $\angle$s).

But $\angle D$ is measured by $\frac{1}{2}$ arc $A C$, § 203

(an inscribed $\angle$ is measured by $\frac{1}{2}$ the intercepted arc);

and $\angle A$ is measured by $\frac{1}{2}$ arc $B D$, § 203

$\therefore \angle C O A$ is measured by $\frac{1}{2}$ arc $A C + \frac{1}{2}$ arc $B D$.

Q. E. D.

Ex. Show that the least chord that can be drawn through a given point in a circle is perpendicular to the diameter drawn through the point.

CASE II.

Let the angle O (Fig. 2) be formed by the two tangents OA and OB.

We are to prove

$\angle O$ *is measured by* $\frac{1}{2}$ arc $AMB - \frac{1}{2}$ arc ASB.

Draw AB.

$\angle ABC = \angle O + \angle OAB$, § 105

(the exterior $\angle$ of a $\triangle$ is equal to the sum of the two opposite interior $\angle$s).

By transposing,

$$\angle O = \angle ABC - \angle OAB.$$

But $\angle ABC$ is measured by $\frac{1}{2}$ arc AMB, § 209

(an $\angle$ formed by a tangent and a chord is measured by $\frac{1}{2}$ the intercepted arc),

and $\angle OAB$ is measured by $\frac{1}{2}$ arc ASB. § 209

$\therefore \angle O$ is measured by $\frac{1}{2}$ arc $AMB - \frac{1}{2}$ arc ASB.

CASE III.

Let the angle O (Fig. 3) be formed by the tangent OB and the secant OA.

We are to prove

$\angle O$ *is measured by* $\frac{1}{2}$ arc $ADS - \frac{1}{2}$ arc CES.

Draw CS.

$\angle ACS = \angle O + \angle CSO$, § 105

(the exterior $\angle$ of a $\triangle$ is equal to the sum of the two opposite interior $\angle$s).

By transposing,

$$\angle O = \angle ACS - \angle CSO.$$

But $\angle ACS$ is measured by $\frac{1}{2}$ arc ADS, § 203

(being an inscribed $\angle$).

and $\angle CSO$ is measured by $\frac{1}{2}$ arc CES, § 209

(being an $\angle$ formed by a tangent and a chord).

$\therefore \angle O$ is measured by $\frac{1}{2}$ arc $ADS - \frac{1}{2}$ arc CES.

Q. E. D.

SUPPLEMENTARY PROPOSITIONS.

PROPOSITION XVIII. THEOREM.

211. *Two parallel lines intercept upon the circumference equal arcs.*

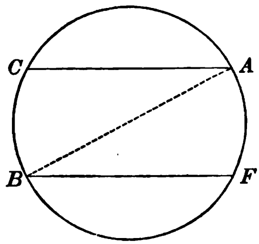


Fig. 1.

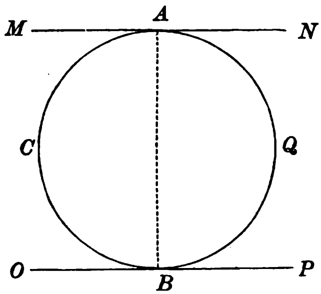


Fig. 2.

Let the two parallel lines CA and BF (Fig. 1), intercept the arcs CB and AF.

We are to prove $\quad$ *arc CB = arc AF.*

Draw AB.

$$\angle A = \angle B, \qquad \S\ 68$$

(being alt.-int. $\angle$s).

But the arc CB is double the measure of $\angle A$.

and the arc AF is double the measure of $\angle B$.

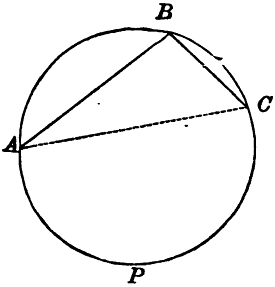
$$\therefore \text{arc } CB = \text{arc } AF. \qquad \text{Ax. } 6$$

Q. E. D.

212. SCHOLIUM. Since two parallel lines intercept on the circumference equal arcs, the two parallel tangents MN and OP (Fig. 2) divide the circumference in two semi-circumferences ACB and AQB, and the line AB joining the points of contact of the two tangents is a diameter of the circle.

PROPOSITION XIX. THEOREM.

213.' *If the sum of two arcs be less than a circumference the greater arc is subtended by the greater chord; and conversely, the greater chord subtends the greater arc.*



In the circle ACP let the two arcs AB and BC together be less than the circumference, and let AB be the greater.

We are to prove chord $AB >$ chord BC.

Draw AC.

In the $\triangle ABC$

$\angle C$, measured by $\frac{1}{2}$ the greater arc AB, § 203

is greater than $\angle A$, measured by $\frac{1}{2}$ the less arc BC.

$\therefore$ the side $AB >$ the side BC, § 117

(*in a $\triangle$ the greater $\angle$ has the greater side opposite to it*).

CONVERSELY: If the chord AB be greater than the chord BC.

We are to prove arc $AB >$ arc BC.

In the $\triangle ABC$,

$AB > BC$, Hyp.

$\therefore \angle C > A$, § 118

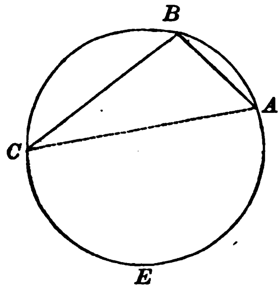
(*in a $\triangle$ the greater side has the greater $\angle$ opposite to it*).

$\therefore$ arc AB, double the measure of the greater $\angle C$, is greater than the arc BC, double the measure of the less $\angle A$.

Q. E. D.

Proposition XX. Theorem.

214. *If the sum of two arcs be greater than a circumference, the greater arc is subtended by the less chord; and, conversely, the less chord subtends the greater arc.*



In the circle BCE let the arcs $AECB$ and $BAEC$ together be greater than the circumference, and let arc $AECB$ be greater than arc $BAEC$.

We are to prove chord $AB <$ chord BC.

From the given arcs take the common arc AEC;

we have left two arcs, CB and AB, less than a circumference,

of which CB is the greater.

$\therefore$ chord $CB >$ chord AB, § 213

(*when the sum of two arcs is less than a circumference, the greater arc is subtended by the greater chord*).

$\therefore$ the chord AB, which subtends the greater arc $AECB$, is less than the chord BC, which subtends the less arc $BAEC$.

Conversely: If the chord AB be less than chord BC.

We are to prove arc $AECB >$ arc $BAEC$.

Arc AB + arc $AECB$ = the circumference.

Arc BC + arc $BAEC$ = the circumference.

$\therefore$ arc AB + arc $AECB$ = arc BC + arc $BAEC$.

But arc $AB <$ arc BC, § 213

(*being subtended by the less chord*).

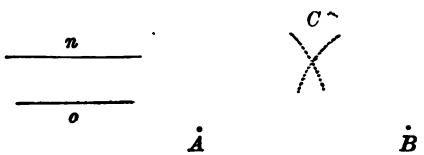
$\therefore$ arc $AECB >$ arc $BAEC$.

Q. E. D.

On Constructions.

Proposition XXI. Problem.

215. *To find a point in a plane, having given its distances from two known points.*



Let A and B be the two known points; n the distance of the required point from A, o its distance from B.

It is required to find a point at the given distances from A and B.

From A as a centre, with a radius equal to n, describe an arc.

From B as a centre, with a radius equal to o, describe an arc intersecting the former arc at C.

C is the required point.

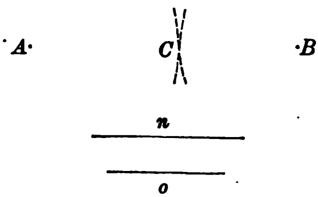
Q. E. F.

216. Corollary 1. By continuing these arcs, another point below the points A and B will be found, which will fulfil the conditions.

217. Cor. 2. When the sum of the given distances is equal to the distance between the two given points, then the two arcs described will be tangent to each other, and the point of tangency will be the point required.

Let the distance from A to B equal $n + o$.

From A as a centre, with a radius equal to n, describe an arc; and from B as a centre, with a radius equal to o, describe an arc.



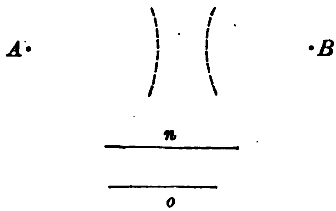
These arcs will touch each other at C, and will not intersect.

$\therefore$ C is the only point which can be found.

218. Scholium 1. The problem is impossible when the distance between the two known points is greater than the sum of the distances of the required point from the two given points.

Let the distance from A to B be greater than $n + o$.

Then from A as a centre, with a radius equal to n, describe an arc;



and from B as a centre, with a radius equal to o, describe an arc.

These arcs will neither touch nor intersect each other;

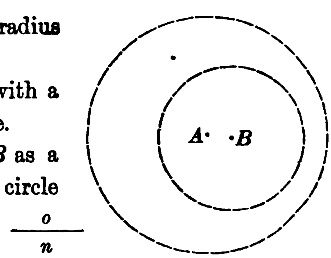
hence they can have no point in common.

219. Scho. 2. The problem is impossible when the distance between the two given points is less than the difference of the distances of the required point from the two given points.

Let the distance from A to B be less than $n - o$.

From A as a centre, with a radius equal to n, describe a circle;

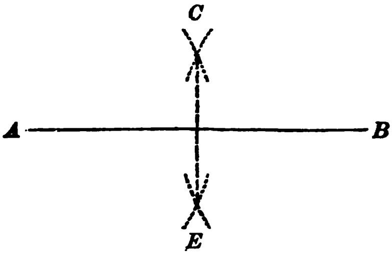
and from B as a centre, with a radius equal to o, describe a circle.



The circle described from B as a centre will fall wholly within the circle described from A as a centre; hence they can have no point in common.

Proposition XXII. Problem.

220. *To bisect a given straight line.*



Let AB be the given straight line.

It is required to bisect the line AB.

From A and B as centres, with equal radii, describe arcs intersecting at C and E.

Join CE.

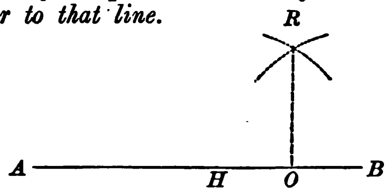
Then the line CE bisects AB.

For, C and E, being two points at equal distances from the extremities A and B, determine the position of a $\perp$ to the middle point of AB. § 60

Q. E. F.

Proposition XXIII. Problem.

221. *At a given point in a straight line, to erect a perpendicular to that line.*



Let O be the given point in the straight line AB.

It is required to erect a $\perp$ to the line AB at the point O.

Take $OH = OB$.

From B and H as centres, with equal radii, describe two arcs intersecting at R.

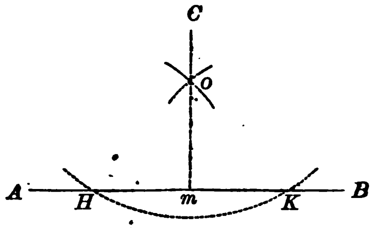
Then the line joining RO is the $\perp$ required.

For, O and R are two points at equal distances from B and H, and $\therefore$ determine the position of a $\perp$ to the line HB at its middle point O. § 60

Q. E. F.

PROPOSITION XXIV. PROBLEM.

222. *From a point without a straight line, to let fall a perpendicular upon that line.*



Let AB be a given straight line, and C a given point without the line.

It is required to let fall a $\perp$ to the line AB from the point C.

From C as a centre, with a radius sufficiently great,

describe an arc cutting AB at the points H and K.

From H and K as centres, with equal radii,

describe two arcs intersecting at O.

Draw CO,

and produce it to meet AB at m.

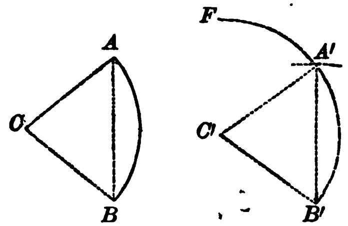
Cm is the $\perp$ required.

For, C and O, being two points at equal distances from H and K, determine the position of a $\perp$ to the line HK at its middle point. § 60

Q. E. F.

PROPOSITION XXV. PROBLEM.

223. *To construct an arc equal to a given arc whose centre is a given point.*



Let C be the centre of the given arc $A\,B$.

It is required to construct an arc equal to arc $A\,B$.

Draw $C\,B$, $C\,A$, and $A\,B$.

From C' as a centre, with a radius equal to $C\,B$,

describe an indefinite arc $B'\,F$.

From B' as a centre, with a radius equal to chord $A\,B$,

describe an arc intersecting the indefinite arc at A'.

Then arc $A'\,B'$ = arc $A\,B$.

For, draw chord $A'\,B'$.

The Ⓢ are equal,

(being described with equal radii),

and chord $A'\,B'$ = chord $A\,B$; Cons.

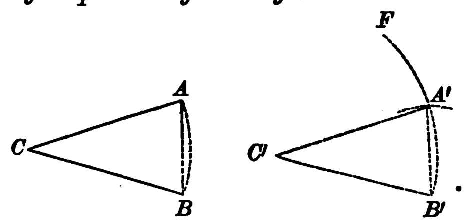
$\therefore$ arc $A'\,B'$ = arc $A\,B$, § 182

(in equal Ⓢ equal chords subtend equal arcs).

Q. E. F.

PROPOSITION XXVI. PROBLEM.

224. *At a given point in a given straight line to construct an angle equal to a given angle.*



Let C' be the given point in the given line $C'B'$, and C the given angle.

It is required to construct an $\angle$ at C' equal to the $\angle$ C.

From C as a centre, with any radius as CB,

describe the arc AB, terminating in the sides of the $\angle$.

Draw chord AB.

From C' as a centre, with a radius equal to CB,

describe the indefinite arc $B'F$.

From B' as a centre, with a radius equal to AB,

describe an arc intersecting the indefinite arc at A'.

Draw $A'C'$.

Then $\angle C' = \angle C$.

For, join $A'B'$.

The Ⓢ to which belong arcs AB and $A'B'$ are equal,
(being described with equal radii).

and chord $A'B' =$ chord AB; Cons.

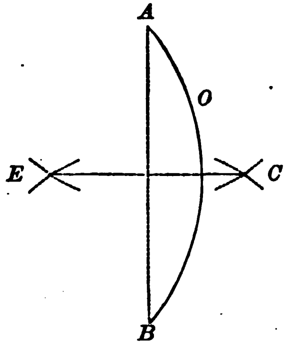
$\therefore$ arc $A'B' =$ arc AB, § 182
(in equal Ⓢ equal chords subtend equal arcs).

$\therefore \angle C' = \angle C$, § 180
(in equal Ⓢ equal arcs subtend equal $\angle$s at the centre).

Q. E. F.

PROPOSITION XXVII. PROBLEM.

225. *To bisect a given arc.*



Let $A\,O\,B$ be the given arc.

It is required to bisect the arc $A\,O\,B$.

Draw the chord $A\,B$.

From A and B as centres, with equal radii,

describe arcs intersecting at E and C.

Draw $E\,C$.

$E\,C$ bisects the arc $A\,O\,B$.

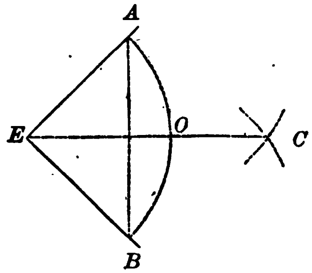
For, E and C, being two points at equal distances from A and B, determine the position of the $\perp$ erected at the middle of chord $A\,B$; § 60

and a $\perp$ erected at the middle of a chord passes through the eentre of the $\odot$, and bisects the arc of the chord. § 184

Q. E. F.

PROPOSITION XXVIII. PROBLEM.

226. *To bisect a given angle.*



Let AEB be the given angle.

It is required to bisect $\angle AEB$.

From E as a centre, with any radius, as EA,

describe the arc AOB, terminating in the sides of the $\angle$.

Draw the chord AB.

From A and B as centres, with equal radii,

describe two arcs intersecting at C.

Join EC.

EC bisects the $\angle E$.

For, E and C, being two points at equal distances from A and B, determine the position of the $\perp$ erected at the middle of AB. § 60

And the $\perp$ erected at the middle of a chord passes through the centre of the $\odot$, and bisects the arc of the chord. § 184

$\therefore$ arc $AO =$ arc OB,

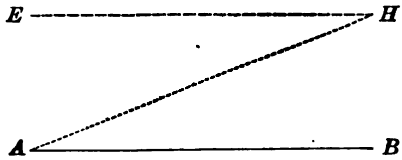
$\therefore \angle AEC = \angle BEC$, § 180

(in the same circle equal arcs subtend equal $\angle$s *at the centre).*

Q. E. F.

Proposition XXIX. Problem.

227. *Through a given point to draw a straight line parallel to a given straight line.*



Let AB be the given line, and H the given point.

It is required to draw through the point H a line $\parallel$ to the line AB.

Draw HA, making the $\angle HAB$.

At the point H construct $\angle AHE = \angle HAB$.

Then the line HE is $\parallel$ to AB.

For, $\angle EHA = \angle HAB$; Cons.

$\therefore HE$ is $\parallel$ to AB, § 69

(when two straight lines, lying in the same plane, are cut by a third straight line, if the alt.-int. $\angle$s be equal, the lines are parallel).

Q. E. F.

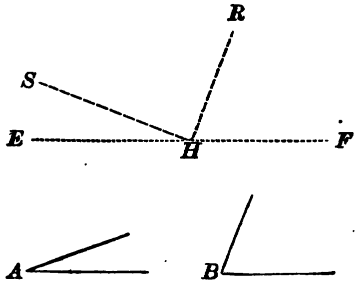
Ex. 1. Find the locus of the centre of a circumference which passes through two given points.

2. Find the locus of the centre of the circumference of a given radius, tangent externally or internally to a given circumference.

3. A straight line is drawn through a given point A, intersecting a given circumference at B and C. Find the locus of the middle point P of the intercepted chord BC.

PROPOSITION XXX. PROBLEM.

228. *Two angles of a triangle being given to find the third.*



Let A and B be two given angles of a triangle.

It is required to find the third $\angle$ of the $\triangle$.

Take any straight line, as EF, and at any point, as H,

construct $\angle RHF$ equal to $\angle B$,

and $\angle SHE$ equal to $\angle A$.

Then $\angle RHS$ is the $\angle$ required.

For, the sum of the three $\angle$s of a $\triangle = 2$ rt. $\angle$s, § 98

and the sum of the three $\angle$s about the point H, on the same side of $EF = 2$ rt. $\angle$s. § 34

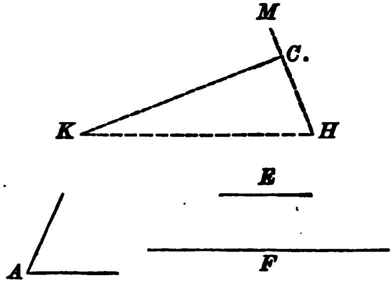
Two $\angle$s of the $\triangle$ being equal to two $\angle$s about the point H, Cons.

the third $\angle$ of the $\triangle$ must be equal to the third $\angle$ about the point H.

Q. E. F.

PROPOSITION XXXI. PROBLEM.

229. *Two sides and the included angle of a triangle being given, to construct the triangle.*



Let the two sides of the triangle be E and F, and the included angle A.

It is required to construct a △ having two sides equal to E and F respectively, and their included ∠ = ∠ A.

Take HK equal to the side F.

At the point H draw the line HM,

making the ∠ KHM = ∠ A.

On HM take HC equal to E.

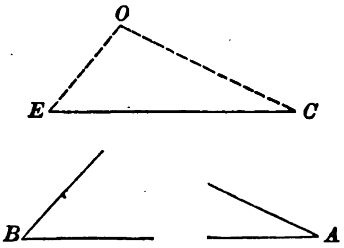
Draw CK.

Then △ CHK is the △ required.

Q. E. F.

Proposition XXXII. Problem.

230. *A side and two adjacent angles of a triangle being given, to construct the triangle.*



Let CE be the given side, A and B the given angles.

It is required to construct a △ having a side equal to C E, and two ∠s adjacent to that side equal to ∠s A and B respectively.

At point C construct an ∠ equal to ∠ A.

At point E construct an ∠ equal to ∠ B.

Produce the sides until they meet at O.

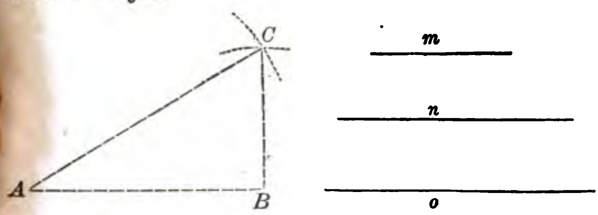
Then △ $C O E$ is the △ required.

Q. E. F.

231. Scholium. The problem is impossible when the two given angles are together equal to, or greater than, two right angles.

PROPOSITION XXXIII. PROBLEM.

232. *The three sides of a triangle being given, to construct the triangle.*



Let the three sides be m, n, and o.

It is required to construct a △ having three sides respectively, equal to m, n, and o.

Draw $A B$ equal to n.

From A as a centre, with a radius equal to o,

describe an arc;

and from B as a centre, with a radius equal to m,

describe an arc intersecting the former arc at C.

Draw $C A$ and $C B$.

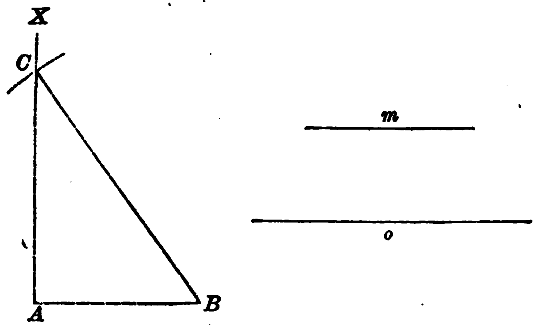
Then △ $C A B$ is the △ required.

Q. E. F.

233. SCHOLIUM. The problem is impossible when one side is *equal to or greater than the sum of the other two.*

PROPOSITION XXXIV. PROBLEM.

234. *The hypotenuse and one side of a right triangle being given, to construct the triangle.*



Let m be the given side, and o the hypotenuse.

It is required to construct a rt. △ having the hypotenuse equal o and one side equal m.

Take $A\,B$ equal to m.

At A erect a ⊥, $A\,X$.

From B as a centre, with a radius equal to o,

describe an arc cutting $A\,X$ at C.

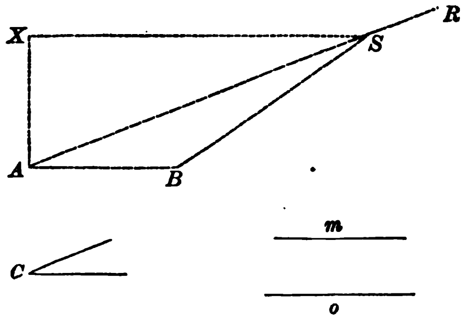
Draw $C\,B$.

Then △ $C\,A\,B$ is the △ required.

Q. E. F.

Proposition XXXV. Problem.

235. *The base, the altitude, and an angle at the base, of a triangle being given, to construct the triangle.*



Let *o* equal the base, *m* the altitude, and *C* the angle at the base.

It is required to construct a △ having the base equal to o, the altitude equal to m, and an ∠ at the base equal to C.

Take $A B$ equal to o.

At the point A, draw the indefinite line $A R$,

making the $\angle B A R = \angle C$.

At the point A, erect a $\perp$ $A X$ equal to m.

From X draw $X S \parallel$ to $A B$,

and meeting the line $A R$ at S.

Draw $S B$.

Then $\triangle A S B$ is the $\triangle$ required.

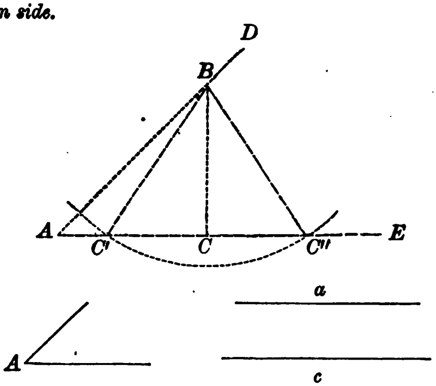
Q. E. F.

Proposition XXXVI. Problem.

236. *Two sides of a triangle and the angle opposite one of them being given, to construct the triangle.*

Case I.

When the given angle is acute, and the side opposite to it is less than the other given side.



Let c **be the longer and** a **the shorter given side, and** $\angle A$ **the given angle.**

It is required to construct a $\triangle$ *having two sides equal to* a *and* c *respectively, and the* $\angle$ *opposite* a *equal to given* $\angle A$.

Construct $\angle DAE$ equal to the given $\angle A$.

On AD take $AB = c$.

From B as a centre, with a radius equal to a,

describe an arc intersecting the side AE at C' and C''.

Draw BC' and BC''.

Then both the $\triangle$s ABC' and ABC'' fulfil the conditions, and hence we have two constructions.

When the given side a is exactly equal to the $\perp$ BC, there will be but one construction, namely, the right triangle ABC.

When the given side a is less than BC, the arc described from B will not intersect AE, and hence the problem is impossible.

CASE II.

When the given angle is acute, right, or obtuse, and the side opposite to it is greater than the other given side.

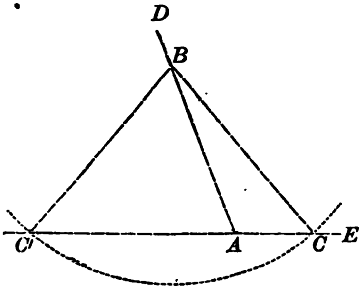


Fig. 1.

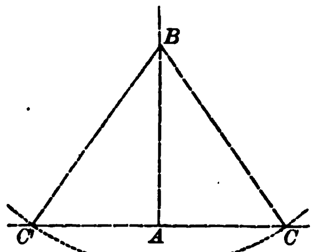
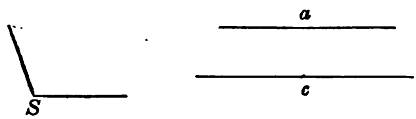


Fig. 2.



When the given angle is obtuse.

Construct the $\angle\, D A E$ (Fig. 1) equal to the given $\angle\, S$.

Take $A B$ equal to a.

From B as a centre, with a radius equal to c,

describe an arc cutting $E A$ at C, and $E A$ produced at C'.

Join $B C$ and $B C'$.

Then the $\triangle\, A B C$ is the $\triangle$ required, and there is only one construction; for the $\triangle\, A B C'$ will not contain the given $\angle\, S$.

When the given angle is acute, as angle $B A C'$.

There is only one construction, namely, the $\triangle\, B A C'$ (Fig. 1).

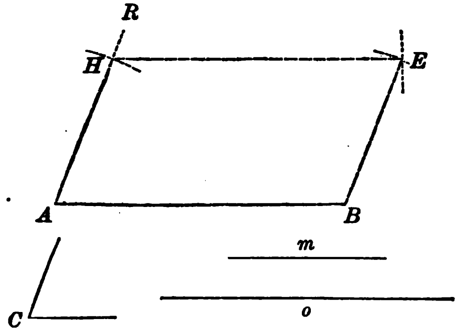
When the given $\angle$ is a right angle.

There are two constructions, the equal $\triangle\triangle\, B A C$ and $B A C'$ (Fig. 2). Q. E. F.

The problem is impossible when the given angle is right or obtuse, if the given side opposite the angle be less than t other given side. §

Proposition XXXVII. Problem.

237. *Two sides and an included angle of a parallelogram being given, to construct the parallelogram.*



Let m and o be the two sides, and C the included angle.

It is required to construct a ▱ having two adjacent sides equal to m and o respectively, and their included ∠ equal to ∠ C.

Draw AB equal to o.

From A draw the indefinite line AR,

making the ∠ A equal to ∠ C.

On AR take AH equal to m.

From H as a centre, with a radius equal to o, describe an arc.

From B as a centre, with a radius equal to m,

describe an arc, intersecting the former arc at E.

Draw EH and EB.

The quadrilateral $ABEH$ is the ▱ required.

For, $AB = HE$, Cons.

$AH = BE$, Cons.

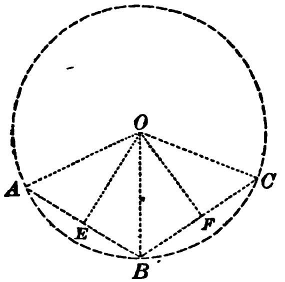
∴ the figure $ABEH$ is a ▱, § 136

(*a quadrilateral, which has its opposite sides equal, is a* ▱).

Q. E. F.

Proposition XXXVIII. Problem.

238. *To describe a circumference through three points not in the same straight line.*



Let the three points be A, B, and C.

It is required to describe a circumference through the three points A, B, and C.

Draw $A B$ and $B C$.

Bisect $A B$ and $B C$.

At the points of bisection, E and F, erect $\perp$s intersecting at O.

From O as a centre, with a radius equal to $O A$, describe a circle.

$\odot\ A B C$ is the $\odot$ required.

For, the point O, being in the $\perp$ $E O$ erected at the middle of the line $A B$, is at equal distances from A and B;

and also, being in the $\perp$ $F O$ erected at the middle of the line $C B$, is at equal distances from B and C, § 58

(every point in the $\perp$ erected at the middle of a straight line is at equal distances from the extremities of that line).

$\therefore$ the point O is at equal distances from A, B, and C,

and a $\odot$ described from O as a centre, with a radius equal to $O A$, will pass through the points A, B, and C.

Q. E. F.

239. Scholium. The same construction serves to describe a circumference which shall pass through the three vertices of a triangle, that is, to circumscribe a circle about a given triangle.

PROPOSITION XXXIX. PROBLEM.

240. *Through a given point to draw a tangent to a given circle.*

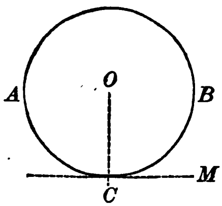


Fig. 1.

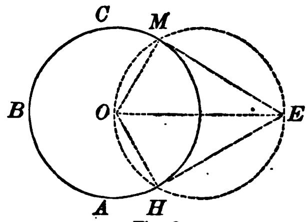


Fig. 2.

CASE 1. — *When the given point is on the circumference.*

Let** ABC **(Fig. 1) be a given circle, and** C **the given point on the circumference.

It is required to draw a tangent to the circle at C.

From the centre O, draw the radius OC.

At the extremity of the radius, C, draw $CM \perp$ to OC.

Then CM is the tangent required, § 186

(a straight line $\perp$ to a radius at its extremity is tangent to the $\odot$).

CASE 2. — *When the given point is without the circumference.*

Let** ABC **(Fig. 2) be the given circle,** O **its centre,** E **the given point without the circumference.

It is required to draw a tangent to the circle ABC from the point E.

Join OE.

On OE as a diameter, describe a circumference intersecting the given circumference at the points M and H.

Draw OM and OH, EM and EH.

Now $\angle OME$ is a rt. $\angle$, § 204

(being inscribed in a semicircle).

$\therefore EM$ is $\perp$ to OM at the point M;

$\therefore EM$ is tangent to the $\odot$, § 186

(a straight line $\perp$ to a radius at its extremity is tangent to the $\odot$).

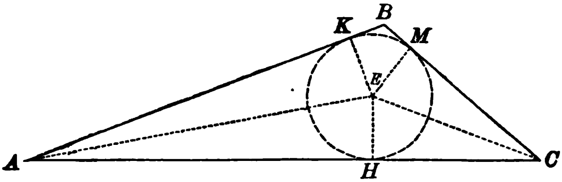
In like manner we may prove HE tangent to the given $\odot$.

Q. E. F.

241. COROLLARY. Two tangents drawn from the same point to a circle are equal.

PROPOSITION XL. PROBLEM.

242. *To inscribe a circle in a given triangle.*



Let ABC be the given triangle.

It is required to inscribe a ⊙ *in the* $\triangle ABC$.

Draw the line AE, bisecting $\angle A$,

and draw the line CE, bisecting $\angle C$.

Draw $EH \perp$ to the line AC.

From E, with radius EH, describe the ⊙ KMH.

The ⊙ KHM is the ⊙ required.

For, draw $EK \perp$ to AB,

and $EM \perp$ to BC.

In the rt. ▲ AKE and AHE

$AE = AE$, Iden.

$\angle EAK = \angle EAH$, Cons.

$\therefore \triangle AKE = \triangle AHE$, § 110

(*Two rt. ▲ are equal if the hypotenuse and an acute $\angle$ of the one be equal respectively to the hypotenuse and an acute $\angle$ of the other*).

$\therefore EK = EH$,

(*being homologous sides of equal ▲*).

In like manner it may be shown $EM = EH$.

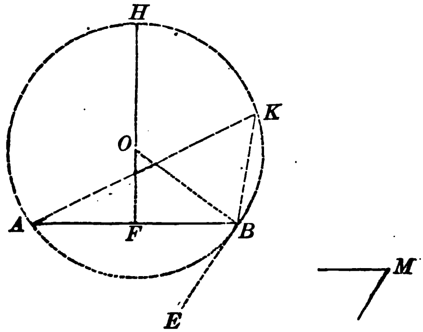
$\therefore EK$, EH, and EM are all equal.

$\therefore$ a ⊙ described from E as a centre, with a radius equal to EH, will touch the sides of the $\triangle$ at points H, K, and M, and be inscribed in the $\triangle$. § 174

Q. E. F.

PROPOSITION XLI. PROBLEM.

243. *Upon a given straight line, to describe a segment which shall contain a given angle.*



Let AB be the given line, and M the given angle.

It is required to describe a segment upon the line AB, which shall contain $\angle M$.

At the point B construct $\angle ABE$ equal to $\angle M$.

Bisect the line AB by the $\perp$ FH.

From the point B, draw $BO \perp$ to EB.

From O, the point of intersection of FH and BO, as a centre, with a radius equal to OB, describe a circumference.

Now the point O, being in a $\perp$ erected at the middle of AB, is at equal distances from A and B, § 58

(*every point in a $\perp$ erected at the middle of a straight line is at equal distances from the extremities of that line*);

$\therefore$ the circumference will pass through A.

Now BE is $\perp$ to OB, Cons.

$\therefore BE$ is tangent to the $\odot$, § 186

(*a straight line $\perp$ to a radius at its extremity is tangent to the* $\odot$).

$\therefore \angle ABE$ is measured by $\frac{1}{2}$ arc AB, § 209

(*being an $\angle$ formed by a tangent and a chord*).

Also any $\angle$ inscribed in the segment AHB, as for instance $\angle AKB$, is measured by $\frac{1}{2}$ arc AB, § 203

(*being an inscribed* $\angle$).

$$\therefore \angle AKB = \angle ABE,$$

(being both measured by ½ the same arc);

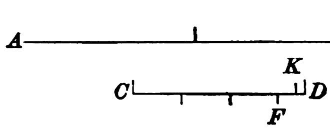
$$\therefore \angle AKB = \angle M.$$

$\therefore$ segment AHB is the segment required.

Q. E. F.

PROPOSITION XLII. PROBLEM.

244. *To find the ratio of two commensurable straight lines.*



Let AB and CD be two straight lines.

It is required to find the greatest common measure of AB and CD, so as to express their ratio in figures.

Apply CD to AB as many times as possible.

Suppose twice with a remainder EB.

Then apply EB to CD as many times as possible.

Suppose three times with a remainder FD.

Then apply FD to EB as many times as possible.

Suppose once with a remainder HB.

Then apply HB to FD as many times as possible.

Suppose once with a remainder KD.

Then apply KD to HB as many times as possible.

Suppose KD is contained just twice in HB.

The measure of each line, referred to KD as a unit, will then be as follows: —

$$\begin{aligned} HB &= 2KD; \\ FD &= HB + KD = 3KD; \\ EB &= FD + HB = 5KD; \\ CD &= 3EB + FD = 18KD; \\ AB &= 2CD + EB = 41KD. \end{aligned}$$

$$\therefore \frac{AB}{CD} = \frac{41KD}{18KD};$$

$$\therefore \text{the ratio of } \frac{AB}{CD} = \frac{41}{18}.$$

Q. E. F.

Exercises.

1. If the sides of a pentagon, no two sides of which are parallel, be produced till they meet; show that the sum of all the angles at their points of intersection will be equal to two right angles.

2. Show that two chords which are equally distant from the centre of a circle are equal to each other; and of two chords, that which is nearer the centre is greater than the one more remote.

3. If through the vertices of an isosceles triangle which has each of the angles at the base double of the third angle, and is inscribed in a circle, straight lines be drawn touching the circle; show that an isosceles triangle will be formed which has each of the angles at the base one-third of the angle at the vertex.

4. ADB is a semicircle of which the centre is C; and AEC is another semicircle on the diameter AC; AT is a common tangent to the two semicircles at the point A. Show that if from any point F, in the circumference of the first, a straight line FC be drawn to C, the part FK, cut off by the second semicircle, is equal to the perpendicular FH to the tangent AT.

5. Show that the bisectors of the angles contained by the opposite sides (produced) of an inscribed quadrilateral intersect at right angles.

6. If a triangle ABC be formed by the intersection of three tangents to a circumference whose centre is O, two of which, AM and AN, are fixed, while the third, BC, touches the circumference at a variable point P; show that the perimeter of the triangle ABC is constant, and equal to $AM + AN$, or $2\,AM$. Also show that the angle BOC is constant.

7. AB is any chord and AC is tangent to a circle at A, CDE a line cutting the circumference in D and E and parallel to AB; show that the triangle ACD is equiangular to the triangle EAB.

CONSTRUCTIONS.

1. Draw two concentric circles, such that the chords of the outer circle which touch the inner may be equal to the diameter of the inner circle.

2. Given the base of a triangle, the vertical angle, and the length of the line drawn from the vertex to the middle point of the base: construct the triangle.

3. Given a side of a triangle, its vertical angle, and the radius of the circumscribing circle: construct the triangle.

4. Given the base, vertical angle, and the perpendicular from the extremity of the base to the opposite side: construct the triangle.

5. Describe a circle cutting the sides of a given square, so that its circumference may be divided at the points of intersection into eight equal arcs.

6. Construct an angle of 60°, one of 30°, one of 120°, one of 150°, one of 45°, and one of 135°.

7. In a given triangle $A\,B\,C$, draw $Q\,D\,E$ parallel to the base $B\,C$ and meeting the sides of the triangle at D and E, so that $D\,E$ shall be equal to $D\,B + E\,C$.

8. Given two perpendiculars, $A\,B$ and $C\,D$, intersecting in O, and a straight line intersecting these perpendiculars in E and F; to construct a square, one of whose angles shall coincide with one of the right angles at O, and the vertex of the opposite angle of the square shall lie in $E\,F$. (Two solutions.)

9. In a given rhombus to inscribe a square.

10. If the base and vertical angle of a triangle be given; find the locus of the vertex.

11. If a ladder, whose foot rests on a horizontal plane and top against a vertical wall, slip down; find the locus of its middle point.

BOOK III.

PROPORTIONAL LINES AND SIMILAR POLYGONS.

On the Theory of Proportion.

245. Def. The *Terms* of a ratio are the quantities compared.

246. Def. The *Antecedent of a ratio* is its first term.

247. Def. The *Consequent of a ratio* is its second term.

248. Def. A *Proportion* is an expression of equality between two equal ratios.

A proportion may be expressed in any one of the following forms:—

1. $a : b :: c : d$

2. $a : b = c : d$

3. $\frac{a}{b} = \frac{c}{d}$.

Form 1 is read, a is to b as c is to d.

Form 2 is read, the ratio of a to b equals the ratio of c to d.

Form 3 is read, a divided by b equals c divided by d.

The *Terms* of a proportion are the four quantities compared.

The *first* and *third* terms in a proportion are the antecedents, the *second* and *fourth* terms are the consequents.

249. The *Extremes* in a proportion are the *first* and *fourth* terms.

250. The *Means* in a proportion are the *second* and *third* terms.

251. Def. In the proportion $a : b :: c : d$; d is a *Fourth Proportional* to a, b, and c.

252. Def. In the proportion $a : b :: b : c$; c is a *Third Proportional* to a and b.

253. Def. In the proportion $a : b :: b : c$; b is a *Mean Proportional* between a and c.

254. Def. Four quantities are *Reciprocally Proportional* when the first is to the second as the reciprocal of the third is to the reciprocal of the fourth.

Thus $$a : b :: \frac{1}{c} : \frac{1}{d}.$$

If we have two quantities a and b, and the reciprocals of these quantities $\frac{1}{a}$ and $\frac{1}{b}$; these four quantities form a *reciprocal proportion*, the first being to the second as the reciprocal of the second is to the reciprocal of the first.

As $$a : b :: \frac{1}{b} : \frac{1}{a}.$$

255. Def. A proportion is taken by *Alternation*, when the means, or the extremes, are made to exchange places.

Thus in the proportion

$$a : b :: c : d,$$

we have either

$$a : c :: b : d, \quad \text{or,} \quad d : b :: c : a.$$

256. Def. A proportion is taken by *Inversion*, when the means and extremes are made to exchange places.

Thus in the proportion

$$a : b :: c : d,$$

by inversion we have

$$b : a :: d : c.$$

257. Def. A proportion is taken by *Composition*, when the sum of the first and second is to the second as the sum of

the third and fourth is to the fourth; or when the sum of the first and second is to the first as the sum of the third and fourth is to the third.

Thus if $a : b :: c : d$,

we have by composition,

$$a + b : b :: c + d : d,$$

or, $$a + b : a :: c + d : c.$$

258. Def. A proportion is taken by *Division*, when the difference of the first and second is to the second as the difference of the third and fourth is to the fourth; or when the difference of the first and second is to the first as the difference of the third and fourth is to the third.

Thus if $a : b :: c : d$,

we have by division

$$a - b : b :: c - d : d,$$

or, $$a - b : a :: c - d : c.$$

Proposition I.

259. *In every proportion the product of the extremes is equal to the product of the means.*

Let $a : b :: c : d$.

We are to prove $ad = bc$.

Now $$\frac{a}{b} = \frac{c}{d},$$

whence, by multiplying by bd,

$$ad = bc.$$

Q. E. D.

In the treatment of proportion, it is assumed that fractions may be found which will *represent* the ratios. It is evident that a ratio may be represented by a fraction when the two quantities compared can be expressed in *integers* in terms of *any common unit.* Thus the ratio of a line $2\frac{1}{3}$ inches long to a line $3\frac{1}{4}$ inches long may be represented by the fraction $\frac{28}{39}$ when both lines are expressed in terms of a unit $\frac{1}{12}$ of an inch long.

But it often happens that no unit exists in terms of which *both* the quantities can be expressed in *integers.* In such cases, however, it is possible to find a fraction that will represent the ratio to *any required degree of accuracy.*

Thus, if a and b denote two incommensurable lines, and b be divided into any integral number (n) of equal parts, if one of these parts be contained in a more than m times, but less than $m+1$ times, then $\frac{a}{b} > \frac{m}{n}$ but $< \frac{m+1}{n}$; so that the error in taking either of these values for $\frac{a}{b}$ is $< \frac{1}{n}$. Since n can be increased at pleasure, $\frac{1}{n}$ can be made less than any assigned value whatever. Propositions, therefore, that are true for $\frac{m}{n}$ and $\frac{m+1}{n}$, however little these fractions differ from each other, are true for $\frac{a}{b}$; and $\frac{m}{n}$ may be taken to *represent* the value of $\frac{a}{b}$.

Proposition II.

260. *A mean proportional between two quantities is equal to the square root of their product.*

In the proportion $a : b :: b : c$,

$$b^2 = a c, \qquad \text{§ 259}$$

(*the product of the extremes is equal to the product of the means*).

Whence, extracting the square root,

$$b = \sqrt{a c}.$$

Q. E. D.

Proposition III.

261. *If the product of two quantities be equal to the product of two others, either two may be made the extremes of a proportion in which the other two are made the means.*

Let $ad = bc$.

We are to prove $a : b :: c : d$.

Divide both members of the given equation by bd.

Then $\frac{a}{b} = \frac{c}{d}$,

or, $a : b :: c : d$.

Q. E. D.

Proposition IV.

262. *If four quantities of the same kind be in proportion, they will be in proportion by alternation.*

Let $a : b :: c : d$.

We are to prove $a : c :: b : d$.

Now, $\frac{a}{b} = \frac{c}{d}$.

Multiply each member of the equation by $\frac{b}{c}$.

Then $\frac{a}{c} = \frac{b}{d}$,

or, $a : c :: b : d$.

Q. E. D.

Proposition V.

263. *If four quantities be in proportion, they will be in proportion by inversion.*

Let $a : b :: c : d.$

We are to prove $b : a :: d : c.$

Now, $$\frac{a}{b} = \frac{c}{d}.$$

Divide 1 by each member of the equation.

Then $$\frac{b}{a} = \frac{d}{c},$$

or, $$b : a :: d : c.$$

Q. E. D.

Proposition VI.

264. *If four quantities be in proportion, they will be in proportion by composition.*

Let $a : b :: c : d$

We are to prove $a + b : b :: c + d : d.$

Now $$\frac{a}{b} = \frac{c}{d}.$$

Add 1 to each member of the equation.

Then $$\frac{a}{b} + 1 = \frac{c}{d} + 1,$$

that is, $$\frac{a+b}{b} = \frac{c+d}{d},$$

or, $$a + b : b :: c + d : d.$$

Q. E. D.

PROPOSITION VII.

265. *If four quantities be in proportion, they will be in proportion by division.*

Let $a : b :: c : d.$

We are to prove $a - b : b :: c - d : d.$

Now $\frac{a}{b} = \frac{c}{d}.$

Subtract 1 from each member of the equation.

Then $\frac{a}{b} - 1 = \frac{c}{d} - 1,$

that is, $\frac{a-b}{b} = \frac{c-d}{d},$

or, $a - b : b :: c - d : d.$

Q. E. D.

PROPOSITION VIII.

266. *In a series of equal ratios, the sum of the antecedents is to the sum of the consequents as any antecedent is to its consequent.*

Let $a : b = c : d = e : f = g : h.$

We are to prove $a + c + e + g : b + d + f + h :: a : b.$

Denote each ratio by r.

Then $r = \frac{a}{b} = \frac{c}{d} = \frac{e}{f} = \frac{g}{h}.$

Whence, $a = br,\quad c = dr,\quad e = fr,\quad g = hr.$

Add these equations.

Then $a + c + e + g = (b + d + f + h)\, r.$

Divide by $(b + d + f + h).$

Then $\frac{a + c + e + g}{b + d + f + h} = r = \frac{a}{b},$

or, $a + c + e + g : b + d + f + h :: a : b.$

Q. E. D.

PROPOSITION IX.

267. *The products of the corresponding terms of two or more proportions are in proportion.*

$$\textit{Let } a : b :: c : d,$$
$$e : f :: g : h,$$
$$k : l :: m : n,$$

We are to prove $aek : bfl :: cgm : dhn.$

Now $\quad \dfrac{a}{b} = \dfrac{c}{d}, \quad \dfrac{e}{f} = \dfrac{g}{h}, \quad \dfrac{k}{l} = \dfrac{m}{n}.$

Whence by multiplication,

$$\frac{aek}{bfl} = \frac{cgm}{dhn},$$

or, $\quad aek : bfl :: cgm : dhn.$

Q. E. D.

PROPOSITION X.

268. *Like powers, or like roots, of the terms of a proportion are in proportion.*

$$\textit{Let } a : b :: c : d.$$

We are to prove $a^n : b^n :: c^n : d^n,$

and $\quad a^{\frac{1}{n}} : b^{\frac{1}{n}} :: c^{\frac{1}{n}} : d^{\frac{1}{n}}.$

Now $\quad \dfrac{a}{b} = \dfrac{c}{d}.$

By raising to the n^{th} power,

$$\frac{a^n}{b^n} = \frac{c^n}{d^n}; \text{ or } a^n : b^n :: c^n : d^n.$$

By extracting the n^{th} root,

$$\frac{a^{\frac{1}{n}}}{b^{\frac{1}{n}}} = \frac{c^{\frac{1}{n}}}{d^{\frac{1}{n}}}; \text{ or, } a^{\frac{1}{n}} : b^{\frac{1}{n}} :: c^{\frac{1}{n}} : d^{\frac{1}{n}}.$$

Q. E. D.

269. DEF. *Equimultiples* of two quantities are the products obtained by multiplying each of them by the same number. Thus ma and mb are equimultiples of a and b.

Proposition XI.

270. *Equimultiples of two quantities are in the same ratio as the quantities themselves.*

Let a and b be any two quantities.

We are to prove $ma : mb :: a : b.$

Now $$\frac{a}{b} = \frac{a}{b}.$$

Multiply both terms of first fraction by m.

Then $$\frac{ma}{mb} = \frac{a}{b},$$

or, $$ma : mb :: a : b.$$

Q. E. D.

Proposition XII.

271. *If two quantities be increased or diminished by like parts of each, the results will be in the same ratio as the quantities themselves.*

Let a and b be any two quantities.

We are to prove $a \pm \frac{p}{q} a : b \pm \frac{p}{q} b :: a : b.$

In the proposition,

$$ma : mb :: a : b,$$

substitute for m, $1 \pm \frac{p}{q}$.

Then $$\left(1 \pm \frac{p}{q}\right) a : \left(1 \pm \frac{p}{q}\right) b :: a : b,$$

or $$a \pm \frac{p}{q} a : b \pm \frac{p}{q} b :: a : b.$$

Q. E. D.

272. Def. Euclid's test of a proportion is as follows:—

"The first of four magnitudes is said to have the same ratio to the second which the third has to the fourth, when any equimultiples whatsoever of the first and third being taken, and any equimultiples whatsoever of the second and fourth;

"If the multiple of the first be *less* than that of the second, the multiple of the third is also less than that of the fourth; or,

"If the multiple of the first be *equal* to that of the second, the multiple of the third is also equal to that of the fourth; or,

"If the multiple of the first be *greater* than that of the second, the multiple of the third is also greater than that of the fourth."

Proposition XIII.

273. *If four quantities be proportional according to the algebraical definition, they will also be proportional according to Euclid's definition.*

Let a, b, c, d be proportional according to the algebraical definition; that is $\frac{a}{b} = \frac{c}{d}$.

We are to prove a, b, c, d, proportional according to Euclid's definition.

Multiply each member of the equality by $\frac{m}{n}$.

Then $$\frac{ma}{nb} = \frac{mc}{nd}.$$

Now from the nature of fractions,

if ma be less than nb, mc will also be less than nd;

if ma be equal to nb, mc will also be equal to nd;

if ma be greater than nb, mc will also be greater than nd.

$\therefore$ a, b, c, d are proportionals according to Euclid's definition.

Q. E. D.

EXERCISES.

1. Show that the straight line which bisects the external vertical angle of an isosceles triangle is parallel to the base.

2. A straight line is drawn terminated by two parallel straight lines; through its middle point any straight line is drawn and terminated by the parallel straight lines. Show that the second straight line is bisected at the middle point of the first.

3. Show that the angle between the bisector of the angle A of the triangle ABC and the perpendicular let fall from A on BC is equal to one-half the difference between the angles B and C.

4. In any right triangle show that the straight line drawn from the vertex of the right angle to the middle of the hypotenuse is equal to one-half the hypotenuse.

5. Two tangents are drawn to a circle at opposite extremities of a diameter, and cut off from a third tangent a portion AB. If C be the centre of the circle, show that ACB is a right angle.

6. Show that the sum of the three perpendiculars from any point within an equilateral triangle to the sides is equal to the altitude of the triangle.

7. Show that the least chord which can be drawn through a given point within a circle is perpendicular to the diameter drawn through the point.

8. Show that the angle contained by two tangents at the extremities of a chord is twice the angle contained by the chord and the diameter drawn from either extremity of the chord.

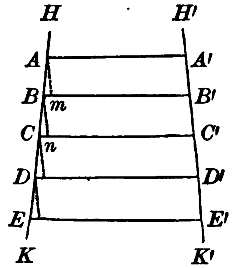
9. If a circle can be inscribed in a quadrilateral; show that the sum of two opposite sides of the quadrilateral is equal to the sum of the other two sides.

10. If the sum of two opposite sides of a quadrilateral be equal to the sum of the other two sides; show that a circle can be inscribed in the quadrilateral.

On Proportional Lines.

Proposition I. Theorem.

274. *If a series of parallels intersecting any two straight lines intercept equal parts on one of these lines, they will intercept equal parts on the other also.*



Let the series of parallels AA', BB', CC', DD', EE', intercept on $H'K'$ equal parts $A'B'$, $B'C'$, $C'D'$, etc.

We are to prove
they intercept on HK equal parts AB, BC, CD, etc.

At points A and B draw Am and Bn ∥ to $H'K'$.

$$Am = A'B', \qquad \S\ 135$$

(*parallels comprehended between parallels are equal*).

$$Bn = B'C', \qquad \S\ 135$$

$$\therefore Am = Bn.$$

In the $\triangle$ BAm and CBn,

$$\angle A = \angle B, \qquad \S\ 77$$

(*having their sides respectively* ∥ *and lying in the same direction from the vertices*).

$$\angle m = \angle n, \qquad \S\ 77$$

and $$Am = Bn,$$

$$\therefore \triangle BAm = \triangle CBn, \qquad \S\ 107$$

(*having a side and two adj.* $\angle$ *of the one equal respectively to a side and two adj.* $\angle$ *of the other*).

$$\therefore AB = BC,$$

(*being homologous sides of equal* $\triangle$).

In like manner we may prove $BC = CD$, etc.

Q. E. D.

Proposition II. Theorem.

275. *If a line be drawn through two sides of a triangle parallel to the third side, it divides those sides proportionally.*

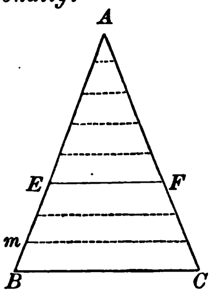


Fig. 1.

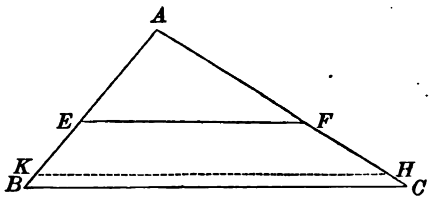


Fig. 2.

In the triangle ABC let EF be drawn parallel to BC.

We are to prove $\dfrac{EB}{AE} = \dfrac{FC}{AF}$.

Case I. — *When AE and EB (Fig. 1) are commensurable.*

Find a common measure of AE and EB, namely Bm.

Suppose Bm to be contained in BE three times,

and in AE five times.

Then $\dfrac{EB}{AE} = \dfrac{3}{5}$.

At the several points of division on BE and AE draw straight lines $\parallel$ to BC.

These lines will divide AC into eight equal parts,

of which FC will contain three, and AF will contain five, § 274

(if parallels intersecting any two straight lines intercept equal parts on one of these lines, they will intercept equal parts on the other also).

$$\therefore \frac{FC}{AF} = \frac{3}{5}.$$

But $\dfrac{EB}{AE} = \dfrac{3}{5}$,

$$\therefore \frac{EB}{AE} = \frac{FC}{AF}. \qquad \text{Ax. 1}$$

CASE. II. — *When AE and EB (Fig. 2) are incommensurable.*

Divide AE into any number of equal parts,

and apply one of these parts to EB as often as it will be contained in EB.

Since AE and EB are incommensurable, a certain number of these parts will extend from E to a point K, leaving a remainder KB, less than one of the parts.

Draw $KH \parallel$ to BC.

Since AE and EK are commensurable,

$$\frac{EK}{AE} = \frac{FH}{AF} \qquad \text{(Case I.)}$$

Suppose the number of parts into which AE is divided to be continually increased, the length of each part will become less and less, and the point K will approach nearer and nearer to B. The limit of EK will be EB, and the limit of FH will be FC.

$$\therefore \text{ the limit of } \frac{EK}{AE} \text{ will be } \frac{EB}{AE},$$

and $$\text{the limit of } \frac{FH}{AF} \text{ will be } \frac{FC}{AF}.$$

Now the variables $\frac{EK}{AE}$ and $\frac{FH}{AF}$ are always equal, however near they approach their limits;

$$\therefore \text{ their limits } \frac{EB}{AE} \text{ and } \frac{FC}{AF} \text{ are equal,} \qquad \S\ 199$$

Q. E. D.

276. COROLLARY. One side of a triangle is to either part cut off by a straight line parallel to the base, as the other side is to the corresponding part.

Now $$EB : AE :: FC : AF. \qquad \S\ 275$$

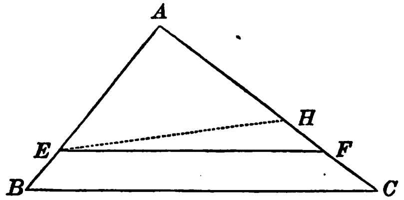
By composition,

$$EB + AE : AE :: FC + AF : AF, \qquad \S\ 263$$

or, $$AB : AE :: AC : AF.$$

PROPOSITION III. THEOREM.

277. *If a straight line divide two sides of a triangle proportionally, it is parallel to the third side.*



In the triangle ABC let EF be drawn so that $\frac{AB}{AE} = \frac{AC}{AF}$.

We are to prove $EF \parallel$ *to* BC.

From E draw $EH \parallel$ to BC.

Then $\frac{AB}{AE} = \frac{AC}{AH}$, § 276

(*one side of a $\triangle$ is to either part cut off by a line $\parallel$ to the base, as the other side is to the corresponding part*).

But $\frac{AB}{AE} = \frac{AC}{AF}$, Hyp.

$\therefore \frac{AC}{AF} = \frac{AC}{AH}$, Ax. 1

$\therefore AF = AH$.

$\therefore EF$ and EH coincide,

(*their extremities being the same points*).

But EH is $\parallel$ to BC; Cons.

$\therefore EF$, which coincides with EH, is $\parallel$ to BC.

Q. E. D.

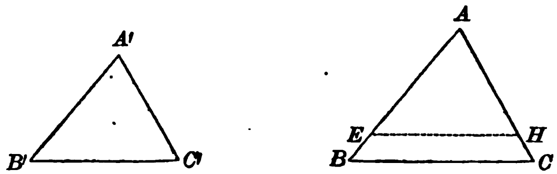
278. DEF. *Similar Polygons* are polygons which have their homologous angles equal and their homologous sides proportional.

Homologous points, lines, and angles, in similar polygons, are points, lines, and angles similarly situated.

On Similar Polygons.

Proposition IV. Theorem.

279. *Two triangles which are mutually equiangular are similar.*



In the $\triangle\triangle$ ABC and $A'B'C'$ let $\angle\angle$ A, B, C be equal to $\angle\angle$ A', B', C' respectively.

We are to prove $AB : A'B' = AC : A'C' = BC : B'C'$.

Apply the $\triangle$ $A'B'C'$ to the $\triangle$ ABC,

so that $\angle$ A' shall coincide with $\angle$ A.

Then the $\triangle$ $A'B'C'$ will take the position of $\triangle$ AEH.

Now $\angle$ AEH (same as $\angle$ B') $= \angle$ B.

$\therefore$ EH is $\parallel$ to BC, § 69

(when two straight lines, lying in the same plane, are cut by a third straight line, if the ext. int. $\angle\angle$ be equal the lines are parallel).

$\therefore AB : AE = AC : AH$, § 276

(one side of a $\triangle$ is to either part cut off by a line $\parallel$ to the base, as the other side is to the corresponding part).

Substitute for AE and AH their equals $A'B'$ and $A'C'$.

Then $AB : A'B' = AC : A'C'$.

In like manner we may prove

$AB : A'B' = BC : B'C'$.

$\therefore$ the two $\triangle\triangle$ are similar. § 278

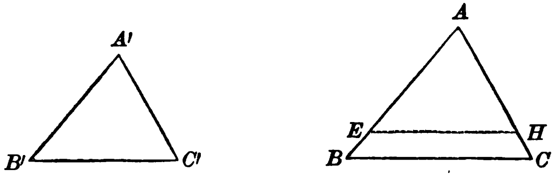
Q. E. D.

280. Cor. 1. Two triangles are similar when two angles of the one are equal respectively to two angles of the other.

281. Cor. 2. Two right triangles are similar when an acute angle of the one is equal to an acute angle of the other.

PROPOSITION V. THEOREM.

282. *Two triangles which have their sides respectively proportional are similar.*



In the triangles ABC and $A'B'C'$ let

$$\frac{AB}{A'B'} = \frac{AC}{A'C'} = \frac{BC}{B'C'}.$$

We are to prove

$\angle$s A, B, and C equal respectively to $\angle$s A', B', and C'.

Take on AB, AE equal to $A'B'$,

and on AC, AH equal to $A'C'$. Draw EH.

$$\frac{AB}{A'B'} = \frac{AC}{A'C'}, \qquad \text{Hyp.}$$

Substitute in this equality, for $A'B'$ and $A'C'$ their equals AE and AH.

Then $$\frac{AB}{AE} = \frac{AC}{AH}.$$

$\therefore EH$ is $\parallel$ to BC, § 277

(*if a line divide two sides of a $\triangle$ proportionally, it is $\parallel$ to the third side*).

Now in the $\triangle$s ABC and AEH

$\angle ABC = \angle AEH$, § 70

(*being ext. int. angles*).

$\angle ACB = \angle AHE$, § 70

$\angle A = \angle A$. Iden.

$\therefore$ $\triangle$s ABC and AEH are similar, § 279

(*two mutually equiangular $\triangle$s are similar*).

$$\therefore \frac{AB}{BC} = \frac{AE}{EH}, \qquad \text{§ 278}$$

(*homologous sides of similar $\triangle$s are proportional*).

But $$\frac{AB}{BC} = \frac{A'B'}{B'C'},$$ Hyp.

$$\therefore \frac{AE}{EH} = \frac{A'B'}{B'C'}.$$ Ax. 1

Since $AE = A'B'$,

$EH = B'C'$. Cons.

Now in the $\triangle$s AEH and $A'B'C'$,

$EH = B'C'$, $AE = A'B'$, and $AH = A'C'$,

$\therefore \triangle AEH = \triangle A'B'C'$, § 108

(*having three sides of the one equal respectively to three sides of the other*).

But $\triangle AEH$ is similar to $\triangle ABC$.

$\therefore \triangle A'B'C'$ is similar to $\triangle ABC$.

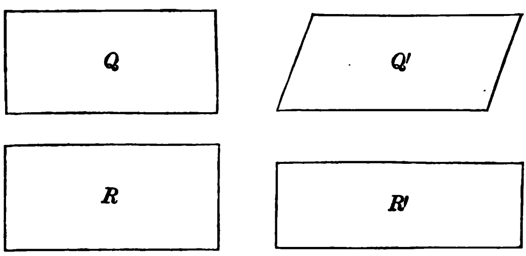
Q. E. D.

283. Scholium. The primary idea of similarity is *likeness of form*; and the two conditions necessary to similarity are:

I. For every angle in one of the figures there must be an equal angle in the other, and

II. the homologous sides must be in proportion.

In the case of *triangles* either condition involves the other, but in the case of *other polygons*, it does not follow that if one condition exist the other does also.

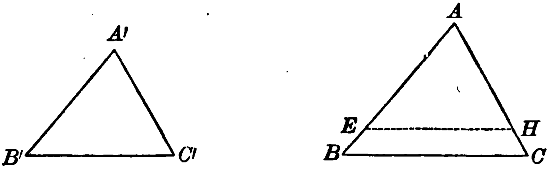


Thus in the quadrilaterals Q and Q', the homologous sides are proportional, but the homologous angles are not equal and the figures are not similar.

In the quadrilaterals R and R', the homologous angles are equal, but the sides are not proportional, and the figures are not similar.

Proposition VI. Theorem.

284. *Two triangles having an angle of the one equal to an angle of the other, and the including sides proportional, are similar.*



In the triangles ABC and $A'B'C'$ let

$$\angle A = \angle A', \text{ and } \frac{AB}{A'B'} = \frac{AC}{A'C'}.$$

We are to prove △s ABC *and* $A'B'C'$ *similar.*

Apply the △ $A'B'C'$ to the △ ABC so that ∠ A' shall coincide with ∠ A.

Then the point B' will fall somewhere upon AB, as at E,

the point C' will fall somewhere upon AC, as at H, and $B'C'$ upon EH.

Now $$\frac{AB}{A'B'} = \frac{AC}{A'C'}.$$ Hyp.

Substitute for $A'B'$ and $A'C'$ their equals AE and AH.

Then $$\frac{AB}{AE} = \frac{AC}{AH}.$$

∴ the line EH divides the sides AB and AC proportionally;

∴ EH is ∥ to BC, § 277

(*if a line divide two sides of a △ proportionally, it is ∥ to the third side*).

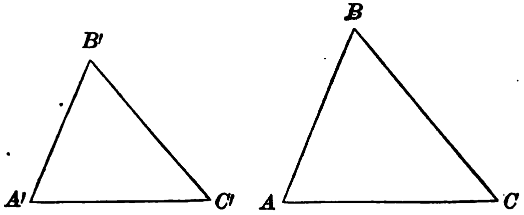
∴ the △s ABC and AEH are mutually equiangular and similar.

∴ △ $A'B'C'$ is similar to △ ABC.

Q. E. D.

PROPOSITION VII. THEOREM.

285. *Two triangles which have their sides respectively parallel are similar.*



In the triangles $A B C$ and $A' B' C'$ let $A B$, $A C$, and $B C$ be parallel respectively to $A' B'$, $A' C'$, and $B' C'$.

We are to prove $\triangle$ *$A B C$ and $A' B' C'$ similar.*

The corresponding $\angle$s are either equal, § 77
(two $\angle$s whose sides are ∥, two and two, and lie in the same direction, or opposite directions, from their vertices are equal).

or supplements of each other, § 78
(if two $\angle$s have two sides ∥ and lying in the same direction from their vertices, while the other two sides are ∥ and lie in opposite directions, the $\angle$s are supplements of each other).

Hence we may make three suppositions:

1st. $A + A' = 2$ rt. $\angle$s, $B + B' = 2$ rt. $\angle$s, $C + C' = 2$ rt. $\angle$s.
2d. $A = A'$, $B + B' = 2$ rt. $\angle$s, $C + C' = 2$ rt. $\angle$s.
3d. $A = A'$, $B = B'$ $\therefore$ $C = C'$.

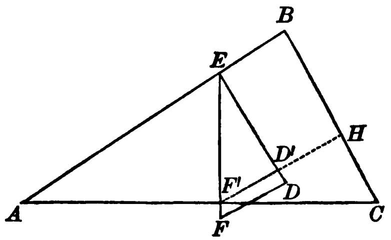
Since the sum of the $\angle$s of the two $\triangle$s cannot exceed *four right angles*, the 3d supposition only is admissible. § 98

$\therefore$ the two $\triangle$s $A B C$ and $A' B' C'$ are similar, § 279
(two mutually equiangular $\triangle$s are similar).

Q. E. D.

PROPOSITION VIII. THEOREM.

286. *Two triangles which have their sides respectively perpendicular to each other are similar.*



In the triangles EFD and BAC, let EF, FD and ED, be perpendicular respectively to AC, BC and AB.

We are to prove $\triangle$s *EFD and BAC similar.*

Place the $\triangle EFD$ so that its vertex E will fall on AB, and the side EF, $\perp$ to AC, will cut AC at F'.

Draw $F'D'$ $\parallel$ to FD, and prolong it to meet BC at H. In the quadrilateral $BED'H$, $\angle$s E and H are rt. $\angle$s.

$\therefore \angle B + \angle ED'H = 2$ rt. $\angle$s. § 158

But $\angle ED'F' + \angle ED'H = 2$ rt. $\angle$s. § 34

$\therefore \angle ED'F' = \angle B.$ Ax. 3.

Now $\angle C + \angle HF'C =$ rt. $\angle$, § 103

(in a rt. $\triangle$ the sum of the two acute $\angle$s = a rt. $\angle$);

and $\angle EF'D' + \angle HF'C =$ rt. $\angle$. Ax. 9.

$\therefore \angle EF'D' = \angle C.$ Ax. 3.

$\therefore$ $\triangle$s $EF'D'$ and BAC are similar. § 280

But $\triangle EFD$ is similar to $\triangle EF'D'$. § 279

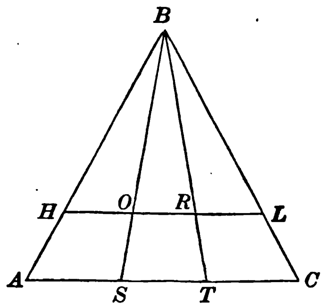
$\therefore$ $\triangle$s EFD and BAC are similar.

Q. E. D.

287. SCHOLIUM. When two triangles have their sides respectively parallel or perpendicular, the parallel sides, or the perpendicular sides, are homologous.

PROPOSITION IX. THEOREM.

288. *Lines drawn through the vertex of a triangle divide proportionally the base and its parallel.*



In the triangle ABC let HL be parallel to AC, and let BS and BT be lines drawn through its vertex to the base.

We are to prove

$$\frac{AS}{HO} = \frac{ST}{OR} = \frac{TC}{RL}.$$

$\triangle$s BHO and BAS are similar, § 279

(*two* $\triangle$s *which are mutually equiangular are similar*).

$\triangle$s BOR and BST are similar, § 279

$\triangle$s BRL and BTC are similar, § 279

$$\therefore \frac{AS}{HO} = \left(\frac{SB}{OB}\right) = \frac{ST}{OR} = \left(\frac{BT}{BR}\right) = \frac{TC}{RL},$$ § 278

(*homologous sides of similar* $\triangle$s *are proportional*).

Q. E. D.

Ex. Show that, if three or more non-parallel straight lines divide two parallels proportionally, they pass through a common point.

PROPOSITION X. THEOREM.

289. *If in a right triangle a perpendicular be drawn from the vertex of the right angle to the hypotenuse:*

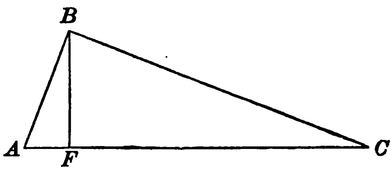
I. *It divides the triangle into two right triangles which are similar to the whole triangle, and also to each other.*

II. *The perpendicular is a mean proportional between the segments of the hypotenuse.*

III. *Each side of the right triangle is a mean proportional between the hypotenuse and its adjacent segment.*

IV. *The squares on the two sides of the right triangle have the same ratio as the adjacent segments of the hypotenuse.*

V. *The square on the hypotenuse has the same ratio to the square on either side as the hypotenuse has to the segment adjacent to that side.*



In the right triangle ABC, let BF be drawn from the vertex of the right angle B, perpendicular to the hypotenuse AC.

I. *We are to prove*

the $\triangle$ ABF, ABC, *and* FBC *similar.*

In the rt. $\triangle$ BAF and BAC,

the acute $\angle A$ is common.

$\therefore$ the $\triangle$ are similar, § 281

(*two rt.* $\triangle$ *are similar when an acute* $\angle$ *of the one is equal to an acute* $\angle$ *of the other*).

In the rt. $\triangle$ BCF and BCA,

the acute $\angle C$ is common.

$\therefore$ the $\triangle$ are similar. § 281

Now as the rt. $\triangle$ ABF and CBF are both similar to ABC, by reason of the equality of their $\angle$s,

they are similar to each other.

II. *We are to prove* $AF : BF :: BF : FC$.

In the similar $\triangle$ ABF and CBF,

AF, the shortest side of the one,
: BF, the shortest side of the other,
: : BF, the medium side of the one,
: FC, the medium side of the other.

III. *We are to prove* $AC : AB :: AB : AF$.

In the similar $\triangle$ ABC and ABF,

AC, the longest side of the one,
: AB, the longest side of the other,
: : AB, the shortest side of the one,
: AF, the shortest side of the other.

Also in the similar $\triangle$ ABC and FBC,

AC, the longest side of the one,
: BC, the longest side of the other,
: : BC, the medium side of the one,
: FC, the medium side of the other.

IV. *We are to prove* $\dfrac{\overline{AB}^2}{\overline{BC}^2} = \dfrac{AF}{FC}$.

In the proportion $AC : AB :: AB : AF$,

$$\overline{AB}^2 = AC \times AF, \qquad \text{§ 259}$$

(*the product of the extremes is equal to the product of the means*).

and in the proportion $AC : BC :: BC : FC$,

$$\overline{BC}^2 = AC \times FC. \qquad \text{§ 259}$$

Dividing the one by the other,

$$\frac{\overline{AB}^2}{\overline{BC}^2} = \frac{AC \times AF}{AC \times FC}.$$

Cancel the common factor AC, and we have

$$\frac{\overline{AB}^2}{\overline{BC}^2} = \frac{AF}{FC}.$$

V. *We are to prove* $\dfrac{\overline{AC}^2}{\overline{AB}^2} = \dfrac{AC}{AF}$.

$$\overline{AC}^2 = AC \times AC.$$

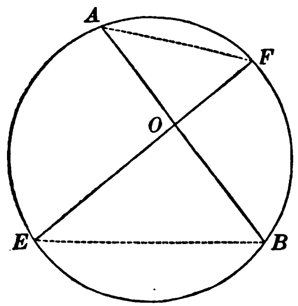
$$\overline{AB}^2 = AC \times AF, \qquad \text{(Case III.)}$$

Divide one equation by the other;

then $$\frac{\overline{AC}^2}{\overline{AB}^2} = \frac{AC \times AC}{AC \times AF} = \frac{AC}{AF}. \qquad \text{Q. E. D.}$$

PROPOSITION XI. THEOREM.

290. *If two chords intersect each other in a circle, their segments are reciprocally proportional.*



Let the two chords AB and EF intersect at the point O.

We are to prove $AO : EO :: OF : OB$.

Draw AF and EB.

In the △ AOF and EOB,

$\angle F = \angle B$, § 203

(*each being measured by* $\frac{1}{2}$ *arc* AE).

$\angle A = \angle E$, § 203

(*each being measured by* $\frac{1}{2}$ *arc* FB).

∴ the △ are similar. § 280

(*two △ are similar when two ∠ of the one are equal to two ∠ of the other*).

Whence AO, the medium side of the one, § 278

: EO, the medium side of the other,

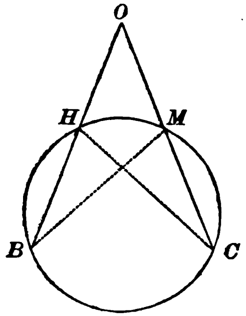
: : OF, the shortest side of the one,

: OB, the shortest side of the other.

Q. E. D.

PROPOSITION XII. THEOREM.

291. *If from a point without a circle two secants be drawn, the whole secants and the parts without the circle are reciprocally proportional.*



Let OB and OC be two secants drawn from point O.

We are to prove $OB : OC :: OM : OH$.

Draw HC and MB.

In the $\triangle$ OHC and OMB

$\angle O$ is common,

$\angle B = \angle C$, § 203

(each being measured by ½ arc HM).

$\therefore$ the two $\triangle$ are similar, § 280

(two $\triangle$ are similar when two $\angle$ of the one are equal to two $\angle$ of the other).

Whence OB, the longest side of the one, § 278

: OC, the longest side of the other,

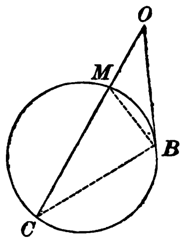
: : OM, the shortest side of the one,

: OH, the shortest side of the other.

Q. E. D.

PROPOSITION XIII. THEOREM.

292. *If from a point without a circle a secant and a tangent be drawn, the tangent is a mean proportional between the whole secant and the part without the circle.*



Let OB be a tangent and OC a secant drawn from the point O to the circle MBC.

We are to prove $OC : OB :: OB : OM$.

Draw BM and BC.

In the $\triangle$ OBM and OBC

$\angle O$ is common.

$\angle OBM$ is measured by $\frac{1}{2}$ arc MB, § 209
(being an $\angle$ formed by a tangent and a chord).

$\angle C$ is measured by $\frac{1}{2}$ arc BM, § 203
(being an inscribed $\angle$).

$\therefore \angle OBM = \angle C.$

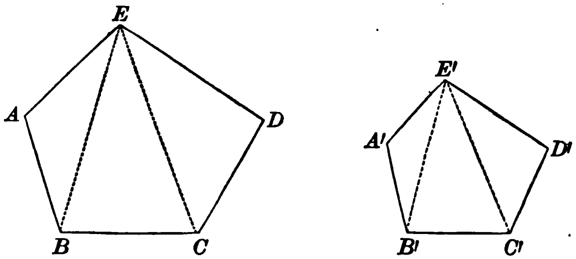
$\therefore$ $\triangle$ OBC and OBM are similar, § 280
(having two $\angle$ of the one equal to two $\angle$ of the other).

Whence OC, the longest side of the one, § 278
: OB, the longest side of the other,
: : OB, the shortest side of the one,
: OM, the shortest side of the other.

Q. E. D.

PROPOSITION XIV. THEOREM.

293. *If two polygons be composed of the same number of triangles which are similar, each to each, and similarly placed, then the polygons are similar.*



In the two polygons $ABCDE$ and $A'B'C'D'E'$, let the triangles BAE, BEC, and CED be similar respectively to the triangles $B'A'E'$, $B'E'C'$, and $C'E'D'$.

We are to prove

the polygon $ABCDE$ similar to the polygon $A'B'C'D'E'$.

$\angle A = \angle A'$, § 278

(being homologous ∠s *of similar* △s *).*

$\angle ABE = \angle A'B'E'$, § 278

$\angle EBC = \angle E'B'C'$, § 278

Add the last two equalities.

Then $\angle ABE + \angle EBC = \angle A'B'E' + \angle E'B'C'$;

or, $\angle ABC = \angle A'B'C'$.

In like manner we may prove $\angle BCD = \angle B'C'D'$, etc.

∴ the two polygons are mutually equiangular.

Now $\dfrac{AE}{A'E'} = \dfrac{AB}{A'B'} = \left(\dfrac{EB}{E'B'}\right) = \dfrac{BC}{B'C'} = \left(\dfrac{EC}{E'C'}\right) = \dfrac{CD}{C'D'} = \dfrac{ED}{E'D'}$,

(the homologous sides of similar △s *are proportional).*

∴ the homologous sides of the two polygons are proportional.

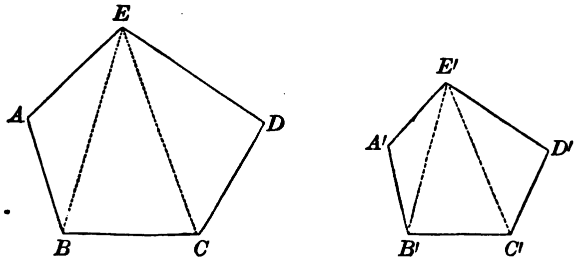
∴ the two polygons are similar, § 278

(having their homologous ∠s *equal, and their homologous sides proportional).*

Q. E. D.

PROPOSITION XV. THEOREM.

294. *If two polygons be similar, they are composed of the same number of triangles, which are similar and similarly placed.*



Let the polygons $ABCDE$ and $A'B'C'D'E'$ be similar.

From two homologous vertices, as E and E',

draw diagonals EB, EC, and $E'B'$, $E'C'$.

We are to prove $\triangle s\ AEB,\ EBC,\ ECD$

similar respectively to $\triangle s\ A'E'B',\ E'B'C',\ E'C'D'$.

In the $\triangle s\ AEB$ and $A'E'B'$,

$$\angle A = \angle A', \qquad \S\ 278$$

(being homologous $\angle s$ *of similar polygons).*

$$\frac{AE}{A'E'} = \frac{AB}{A'B'}, \qquad \S\ 278$$

(being homologous sides of similar polygons).

$\therefore \triangle s\ AEB$ and $A'E'B'$ are similar, § 284

(having an $\angle$ *of the one equal to an* $\angle$ *of the other, and the including sides proportional).*

Also, $\angle ABC = \angle A'B'C'$,

(being homologous $\angle s$ *of similar polygons).*

$$\angle ABE = \angle A'B'E',$$

(being homologous $\angle s$ *of similar* $\triangle s$ *).*

$$\therefore \angle ABC - \angle ABE = \angle A'B'C' - \angle A'B'E'.$$

That is $\angle EBC = \angle E'B'C'$.

Now $$\frac{EB}{E'B'} = \frac{AB}{A'B'},$$
(*being homologous sides of similar* $\triangle$);

also $$\frac{BC}{B'C'} = \frac{AB}{A'B'},$$
(*being homologous sides of similar polygons*).

$$\therefore \frac{EB}{E'B'} = \frac{BC}{B'C'},$$ Ax. 1

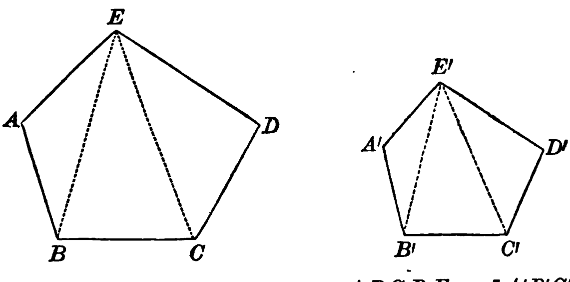
$\therefore$ $\triangle$ EBC and $E'B'C'$ are similar, § 284
(*having an* $\angle$ *of the one equal to an* $\angle$ *of the other, and the including sides proportional*).

In like manner we may prove $\triangle\, ECD$ similar to $\triangle\, E'C'D'$.

Q. E. D.

PROPOSITION XVI. THEOREM.

295. *The perimeters of two similar polygons have the same ratio as any two homologous sides.*



Let the two similar polygons be $ABCDE$ and $A'B'C'D'E'$, and let P and P' represent their perimeters.

We are to prove $P : P' :: AB : A'B'$.

$AB : A'B' :: BC : B'C' :: CD : C'D'$ etc. § 278
(*the homologous sides of similar polygons are proportional*).

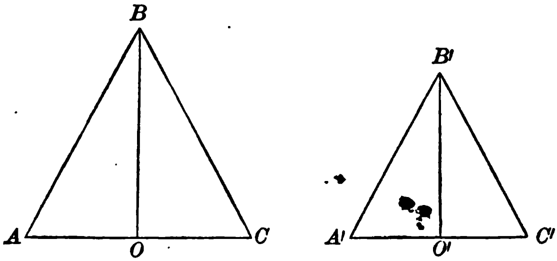
$\therefore AB + BC$, etc. $: A'B' + B'C'$, etc. $:: AB : A'B'$, § 266
(*in a series of equal ratios the sum of the antecedents is to the sum of the consequents as any antecedent is to its consequent*).

That is $P : P' :: AB : A'B'$.

Q. E. D.

Proposition XVII. Theorem.

296. *The homologous altitudes of two similar triangles have the same ratio as any two homologous sides.*



In the two similar triangles ABC and $A'B'C'$, let the altitudes be BO and $B'O'$.

We are to prove $\dfrac{BO}{B'O'} = \dfrac{AB}{A'B'}$.

In the rt. $\triangle$s BOA and $B'O'A'$,

$$\angle A = \angle A' \qquad \S\ 278$$

(*being homologous* $\angle$s *of the similar* $\triangle$s ABC *and* $A'B'C'$).

$\therefore \triangle BOA$ and $\triangle B'O'A'$ are similar, § 281

(*two rt.* $\triangle$s *having an acute* $\angle$ *of the one equal to an acute* $\angle$ *of the other are similar*).

$\therefore$ their homologous sides give the proportion

$$\frac{BO}{B'O'} = \frac{AB}{A'B'}.$$

Q. E. D.

297. Cor. 1. The homologous altitudes of similar triangles have the same ratio as their homologous bases.

In the similar $\triangle$ $A B C$ and $A' B' C'$,

$$\frac{A C}{A' C'} = \frac{A B}{A' B'}, \qquad \S\ 278$$

(*the homologous sides of similar* $\triangle$ *are proportional*).

And in the similar $\triangle$ $B O A$ and $B' O' A'$,

$$\frac{B O}{B' O'} = \frac{A B}{A' B'}, \qquad \S\ 296$$

$$\therefore \frac{B O}{B' O'} = \frac{A C}{A' C'}, \qquad \text{Ax. 1}$$

298. Cor. 2. The homologous altitudes of similar triangles have the same ratio as their perimeters.

Denote the perimeter of the first by P, and that of the second by P'.

Then $$\frac{P}{P'} = \frac{A B}{A' B'}, \qquad \S\ 295$$

(*the perimeters of two similar polygons have the same ratio as any two homologous sides*).

But $$\frac{B O}{B' O'} = \frac{A B}{A' B'}, \qquad \S\ 296$$

$$\therefore \frac{B O}{B' O'} = \frac{P}{P'}. \qquad \text{Ax. 1}$$

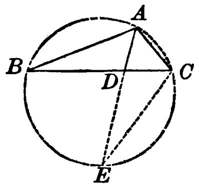
Ex. 1. If any two straight lines be cut by parallel lines, show that the corresponding segments are proportional.

2. If the four sides of any quadrilateral be bisected, show that the lines joining the points of bisection will form a parallelogram.

3. Two circles intersect; the line $A H K B$ joining their centres A, B, meets them in H, K. On $A B$ is described an equilateral triangle $A B C$, whose sides $B C$, $A C$, intersect the circles in F, E. $F E$ produced meets $B A$ produced in P. Show that as $P A$ is to $P K$ so is $C F$ to $C E$, and so also is $P H$ to $P B$.

Proposition XVIII. Theorem.

299. *In any triangle the product of two sides is equal to the product of the segments of the third side formed by the bisector of the opposite angle together with the square of the bisector.*



Let $\angle BAC$ of the $\triangle ABC$ be bisected by the straight line AD.

We are to prove $BA \times AC = BD \times DC + \overline{AD}^2$.

Describe the $\odot ABC$ about the $\triangle ABC$;

produce AD to meet the circumference in E, and draw EC.

Then in the $\triangle$s ABD and AEC,

$\angle BAD = \angle CAE$, Hyp.

$\angle B = \angle E$, § 203

(*each being measured by $\frac{1}{2}$ the arc AC*).

$\therefore$ $\triangle$s ABD and AEC are similar, § 280

(*two $\triangle$s are similar when two $\angle$s of the one are equal respectively to two $\angle$s of the other*).

Whence BA, the longest side of the one,
: EA, the longest side of the other,
: : AD, the shortest side of the one,
: AC, the shortest side of the other;

or, $$\frac{BA}{EA} = \frac{AD}{AC},$$ § 278

(*homologous sides of similar $\triangle$s are proportional*).

$\therefore BA \times AC = EA \times AD$.

But $EA \times AD = (ED + AD)\, AD$,

$\therefore BA \times AC = ED \times AD + \overline{AD}^2$.

But $ED \times AD = BD \times DC$, § 290

(*the segments of two chords in a $\odot$ which intersect each other are reciprocally proportional*).

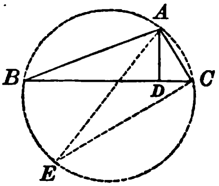
Substitute in the above equality $BD \times DC$ for $ED \times AD$,

then $BA \times AC = BD \times DC + \overline{AD}^2$.

Q. E. D.

Proposition XIX. Theorem.

300. *In any triangle the product of two sides is equal to the product of the diameter of the circumscribed circle by the perpendicular let fall upon the third side from the vertex of the opposite angle.*



Let ABC be a triangle, and AD the perpendicular from A to BC.

Describe the circumference ABC about the $\triangle ABC$.

Draw the diameter AE, and draw EC.

We are to prove $BA \times AC = EA \times AD$.

In the $\triangle$s ABD and AEC

$\angle BDA$ is a rt. $\angle$, Cons.

$\angle ECA$ is a rt. $\angle$, § 204
(being inscribed in a semicircle).

$\therefore \angle BDA = \angle ECA$.

$\angle B = \angle E$, § 203
(each being measured by $\frac{1}{2}$ the arc AC).

$\therefore$ $\triangle$s ABD and AEC are similar, § 281
(two rt. $\triangle$s having an acute $\angle$ of the one equal to an acute $\angle$ of the other are similar).

Whence BA, the longest side of the one,
: EA, the longest side of the other,
: : AD, the shortest side of the one,
: AC, the shortest side of the other;

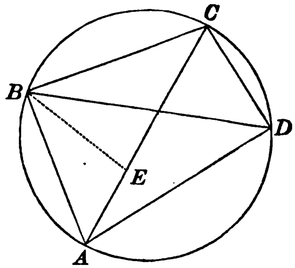
or, $$\frac{BA}{EA} = \frac{AD}{AC}.$$ § 278

$\therefore BA \times AC = EA \times AD$.

Q. E. D.

PROPOSITION XX. THEOREM.

301. *The product of the two diagonals of a quadrilateral inscribed in a circle is equal to the sum of the products of its opposite sides.*



Let $ABCD$ be any quadrilateral inscribed in a circle, AC and BD its diagonals.

We are to prove $BD \times AC = AB \times CD + AD \times BC$.

Construct $\angle ABE = \angle DBC$,

and add to each $\angle EBD$.

Then in the $\triangle$ ABD and BCE,

$\angle ABD = \angle CBE$, Ax. 2

and $\angle BDA = \angle BCE$, § 203

(*each being measured by $\frac{1}{2}$ the arc AB*).

$\therefore$ $\triangle$ ABD and BCE, are similar, § 280

(*two $\triangle$ are similar when two $\angle$ of the one are equal respectively to two $\angle$ of the other*).

Whence AD, the medium side of the one,

: CE, the medium side of the other,

: : BD, the longest side of the one,

: BC, the longest side of the other,

or, $$\frac{AD}{CE} = \frac{BD}{BC},$$ § 278

(*the homologous sides of similar* △ *are proportional*).

$$\therefore BD \times CE = AD \times BC.$$

Again, in the △ ABE and BCD,

$$\angle ABE = \angle DBC,$$ Cons.

and $$\angle BAE = \angle BDC,$$ § 203

(*each being measured by* ½ *of the arc* BC).

$\therefore$ △ ABE and BCD are similar, § 280

(*two* △ *are similar when two* ∠ *of the one are equal respectively to two* ∠ *of the other*).

Whence AB, the longest side of the one,

: BD, the longest side of the other,

: : AE, the shortest side of the one,

: CD, the shortest side of the other.

or, $$\frac{AB}{BD} = \frac{AE}{CD},$$ § 278

(*the homologous sides of similar* △ *are proportional*).

$$\therefore BD \times AE = AB \times CD.$$

But $$BD \times CE = AD \times BC.$$

Adding these two equalities,

$$BD\,(AE + CE) = AB \times CD + AD \times BC,$$

or $$BD \times AC = AB \times CD + AD \times BC.$$

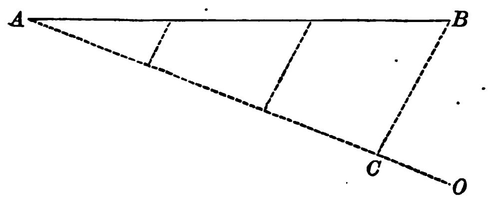
Q. E. D.

Ex. If two circles are tangent internally, show that chords of the greater, drawn from the point of tangency, are divided proportionally by the circumference of the less.

On Constructions.

Proposition XXI. Problem.

302. *To divide a given straight line into equal parts.*



Let AB be the given straight line.

It is required to divide AB into equal parts.

From A draw the indefinite line AO.

Take any convenient length, and apply it to AO as many times as the line AB is to be divided into parts.

From the last point thus found on AO, as C, draw CB.

Through the several points of division on AO draw lines ∥ to CB.

These lines divide AB into equal parts, § 274

(*if a series of* ∥s *intersecting any two straight lines, intercept equal parts on one of these lines, they intercept equal parts on the other also*).

Q. E. F.

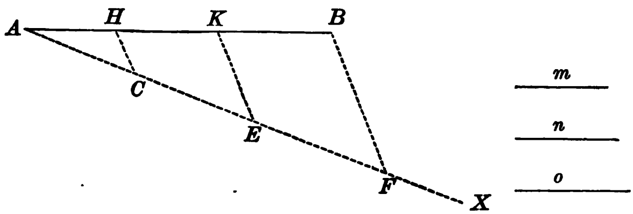
Ex. To draw a common tangent to two given circles.

I. When the common tangent is *exterior*.

II. When the common tangent is *interior*.

Proposition XXII. Problem.

303. *To divide a given straight line into parts proportional to any number of given lines.*



Let AB, m, n, and o be given straight lines.

It is required to divide AB into parts proportional to the given lines m, n, and o.

Draw the indefinite line AX.

On AX take $AC = m$,

$CE = n$,

and $EF = o$.

Draw FB. From E and C draw EK and CH ∥ to FB.

K and H are the division points required.

For $$\left(\frac{AK}{AE}\right) = \frac{AH}{AC} = \frac{HK}{CE} = \frac{KB}{EF},$$ § 275

(a line drawn through two sides of a △ ∥ to the third side divides those sides proportionally).

$$\therefore AH : HK : KB :: AC : CE : EF.$$

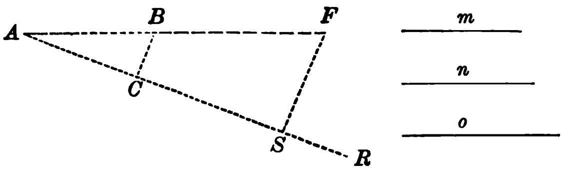
Substitute m, n, and o for their equals AC, CE, and EF.

Then $AH : HK : KB :: m : n : o$.

Q. E. F.

Proposition XXIII. Problem.

304. *To find a fourth proportional to three given straight lines.*



Let the three given lines be m, n, and o.

It is required to find a fourth proportional to m, n, and o.

Take AB equal to n.

Draw the indefinite line AR, making any convenient $\angle$ with AB.

On AR take $AC = m$, and $CS = o$.

Draw CB.

From S draw $SF \parallel$ to CB, to meet AB produced at F.

BF is the fourth proportional required.

For, $AC : AB :: CS : BF$, § 275

(*a line drawn through two sides of a* $\triangle \parallel$ *to the third side divides those sides proportionally*).

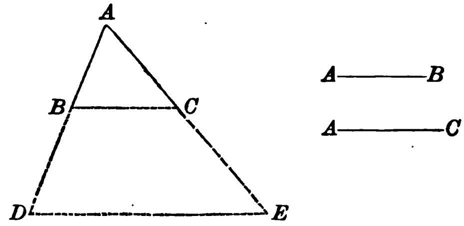
Substitute m, n, and o for their equals AC, AB, and CS.

Then $m : n :: o : BF$.

Q. E. F.

Proposition XXIV. Problem.

305. *To find a third proportional to two given straight lines.*



Let AB and AC be the two given straight lines.

It is required to find a third proportional to AB and AC.

Place AB and AC so as to contain any convenient $\angle$.

Produce AB to D, making $BD = AC$.

Join BC.

Through D draw $DE \parallel$ to BC to meet AC produced at E.

CE is a third proportional to AB and AC. § 251

For, $$\frac{AB}{BD} = \frac{AC}{CE},$$ § 275

(*a line drawn through two sides of a* $\triangle \parallel$ *to the third side divides those sides proportionally*).

Substitute, in the above equality, AC for its equal BD;

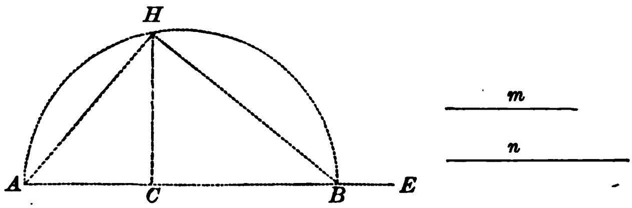
Then $$\frac{AB}{AC} = \frac{AC}{CE},$$

or, $$AB : AC :: AC : CE.$$

Q. E. F.

PROPOSITION XXV. PROBLEM.

306. *To find a mean proportional between two given lines.*



Let the two given lines be m and n.

It is required to find a mean proportional between m and n.

On the straight line AE

take $AC = m$, and $CB = n$.

On AB as a diameter describe a semi-circumference.

At C erect the $\perp$ CH.

CH is a mean proportional between m and n.

Draw HB and HA.

The $\angle AHB$ is a rt. $\angle$, § 204

(being inscribed in a semicircle),

and HC is a $\perp$ let fall from the vertex of a rt. $\angle$ to the hypotenuse.

$\therefore AC : CH :: CH : CB$, § 289

(the $\perp$ let fall from the vertex of the rt. $\angle$ to the hypotenuse is a mean proportional between the segments of the hypotenuse).

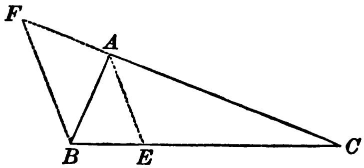
Substitute for AC and CB their equals m and n.

Then $m : CH :: CH : n$. Q. E. F.

307. COROLLARY. *If from a point in the circumference a perpendicular be drawn to the diameter, and chords from the point to the extremities of the diameter, the perpendicular is a mean proportional between the segments of the diameter, and each chord is a mean proportional between its adjacent segment and the diameter.*

Proposition XXVI. Problem.

308. *To divide one side of a triangle into two parts proportional to the other two sides.*



Let ABC be the triangle.

It is required to divide the side BC into two such parts that the ratio of these two parts shall equal the ratio of the other two sides, AC and AB.

Produce CA to F, making $AF = AB$.

Draw FB.

From A draw $AE \parallel$ to FB.

E is the division point required.

For $$\frac{CA}{AF} = \frac{CE}{EB}. \qquad \S\ 275$$

(a line drawn through two sides of a $\triangle \parallel$ to the third side divides those sides proportionally).

Substitute for AF its equal AB.

Then $$\frac{CA}{AB} = \frac{CE}{EB}.$$

Q. E. F.

309. Corollary. The line AE bisects the angle CAB.

For $$\angle F = \angle ABF, \qquad \S\ 112$$

(being opposite equal sides).

$$\angle F = \angle CAE, \qquad \S\ 70$$

(being ext.-int. $\angle$s).

$$\angle ABF = \angle BAE, \qquad \S\ 68$$

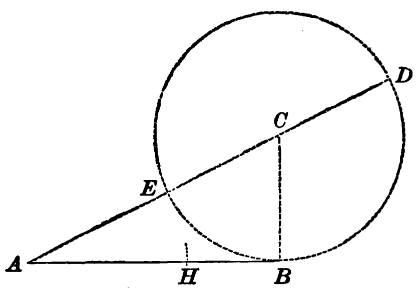
(being alt.-int. $\angle$s).

$$\therefore \angle CAE = \angle BAE. \qquad \text{Ax. } 1$$

310. Def. A straight line is said to be divided *in extreme and mean ratio,* when the whole line is to the greater segment as the greater segment is to the less.

PROPOSITION XXVII. PROBLEM.

311. *To divide a given line in extreme and mean ratio.*



Let AB be the given line.

It is required to divide AB in extreme and mean ratio.

At B erect a $\perp$ BC, equal to one-half of AB.

From C as a centre, with a radius equal to CB, describe a $\odot$.

Since AB is $\perp$ to the radius CB at its extremity, it is tangent to the circle.

Through C draw AD, meeting the circumference in E and D.

On AB take $AH = AE$.

H is the division point of AB required.

For $AD : AB :: AB : AE$, § 292

(if from a point without the circumference a secant and a tangent be drawn, the tangent is a mean proportional between the whole secant and the part without the circumference).

Then $AD - AB : AB :: AB - AE : AE$. § 265

Since $AB = 2\,CB$, Cons.

and $ED = 2\,CB$,

(the diameter of a ⊙ being twice the radius),

$$AB = ED. \qquad \text{Ax. 1}$$

$$\therefore AD - AB = AD - ED = AE.$$

But $AE = AH$, Cons.

$$\therefore AD - AB = AH. \qquad \text{Ax. 1}$$

Also $AB - AE = AB - AH = HB.$

Substitute these equivalents in the last proportion.

Then $AH : AB :: HB : AH.$

Whence, by inversion, $AB : AH :: AH : HB.$ § 263

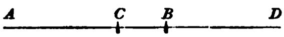
$\therefore AB$ is divided at H in extreme and mean ratio.

Q. E. F.

REMARK. AB is said to be divided at H, *internally*, in extreme and mean ratio. If BA be produced to H', making AH' equal to AD, AB is said to be divided at H', *externally*, in extreme and mean ratio.

Prove $AB : AH' :: AH' : H'B.$

When a line is divided internally and externally in the *same ratio*, it is said to be divided *harmonically*.

Thus AB 

is divided harmonically at C and D, if $CA : CB :: DA : DB$; that is, if the ratio of the distances of C from A and B is equal to the ratio of the distances of D from A and B.

This proportion taken by alternation gives:

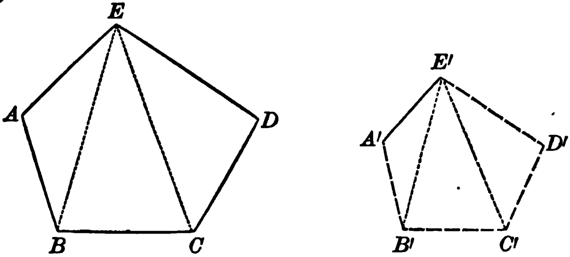
$AC : AD :: BC : BD$; that is, CD is divided harmonically at the points B and A. The four points A, B, C, D, are called *harmonic points*; and the two pairs A, B, and C, D, are called *conjugate points*.

Ex. 1. To divide a given line harmonically in a given ratio.

2. To find the locus of all the points whose distances from two given points are in a given ratio.

PROPOSITION XXVIII. PROBLEM.

312. *Upon a given line homologous to a given side of a given polygon, to construct a polygon similar to the given polygon.*



Let $A'E'$ be the given line, homologous to AE of the given polygon $ABCDE$.

It is required to construct on $A'E'$ a polygon similar to the given polygon.

From E draw the diagonals EB and EC.

From E' draw $E'B'$, making $\angle A'E'B' = \angle AEB$.

Also from A' draw $A'B'$, making $\angle B'A'E' = \angle BAE$,

and meeting $E'B'$ at B'.

The two $\triangle$ ABE and $A'B'E'$ are similar, § 280

(*two $\triangle$ are similar if they have two $\angle$ of the one equal respectively to two $\angle$ of the other*).

Also from E' draw $E'C'$, making $\angle B'E'C' = \angle BEC$.

From B' draw $B'C'$, making $\angle E'B'C' = \angle EBC$,

and meeting $E'C'$ at C'.

Then the two $\triangle$ EBC and $E'B'C'$ are similar, § 280

(*two $\triangle$ are similar if they have two $\angle$ of the one equal respectively to two $\angle$ of the other*).

In like manner construct $\triangle$ $E'C'D'$ similar to $\triangle$ ECD.

Then the two polygons are similar, § 293

(*two polygons composed of the same number of $\triangle$ similar to each other and similarly placed, are similar*).

$\therefore$ $A'B'C'D'E'$ is the required polygon.

Q. E. F.

Exercises.

1. $A B C$ is a triangle inscribed in a circle, and $B D$ is drawn to meet the tangent to the circle at A in D, at an angle $A B D$ equal to the angle $A B C$; show that $A C$ is a fourth proportional to the lines $B D$, $A D$, $A B$.

2. Show that either of the sides of an isosceles triangle is a mean proportional between the base and the half of the segment of the base, produced if necessary, which is cut off by a straight line drawn from the vertex at right angles to the equal side.

3. $A B$ is the diameter of a circle, D any point in the circumference, and C the middle point of the arc $A D$. If $A C$, $A D$, $B C$ be joined and $A D$ cut $B C$ in E, show that the circle circumscribed about the triangle $A E B$ will touch $A C$ and its diameter will be a third proportional to $B C$ and $A B$.

4. From the obtuse angle of a triangle draw a line to the base, which shall be a mean proportional between the segments into which it divides the base.

5. Find the point in the base produced of a right triangle, from which the line drawn to the angle opposite to the base shall have the same ratio to the base produced which the perpendicular has to the base itself.

6. A line touching two circles cuts another line joining their centres; show that the segments of the latter will be to each other as the diameters of the circles.

7. Required the locus of the middle points of all the chords of a circle which pass through a fixed point.

8. O is a fixed point from which any straight line is drawn meeting a fixed straight line at P; in $O P$ a point Q is taken such that $O Q$ is to $O P$ in a fixed ratio. Determine the locus of Q.

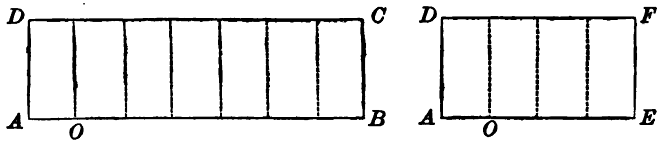
9. O is a fixed point from which any straight line is drawn meeting the circumference of a fixed circle at P; in $O P$ a point Q is taken such that $O Q$ is to $O P$ in a fixed ratio. Determine the locus of Q.

BOOK IV.

COMPARISON AND MEASUREMENT OF THE SURFACES OF POLYGONS.

Proposition I. Theorem.

313. *Two rectangles having equal altitudes are to each other as their bases.*



Let the two rectangles be AC and AF, having the the same altitude AD.

We are to prove $\dfrac{\text{rect. } AC}{\text{rect. } AF} = \dfrac{AB}{AE}$.

Case I. — *When AB and AE are commensurable.*

Find a common divisor of the bases AB and AE, as AO.

Suppose AO to be contained in AB seven times and in AE four times.

Then $$\frac{AB}{AE} = \frac{7}{4}.$$

At the several points of division on AB and AE erect $\perp$s.

The rect. AC will be divided into seven rectangles,

and rect. AF will be divided into four rectangles.

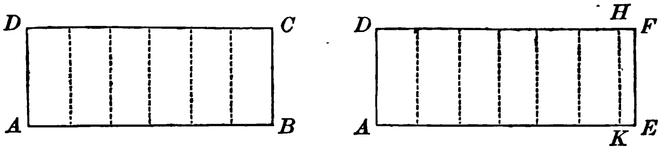
These rectangles are all equal, for they may be applied to each other and will coincide throughout.

$$\therefore \frac{\text{rect } AC}{\text{rect } AF} = \frac{7}{4}.$$

But $$\frac{AB}{AE} = \frac{7}{4}.$$

$$\therefore \frac{\text{rect } AC}{\text{rect } AF} = \frac{AB}{AE}.$$

CASE II. — *When AB and AE are incommensurable.*



Divide AB into any number of equal parts, and apply one of these parts to AE as often as it will be contained in AE.

Since AB and AE are incommensurable, a certain number of these parts will extend from A to a point K, leaving a remainder KE less than one of these parts.

Draw $KH \parallel$ to EF.

Since AB and AK are commensurable,

$$\frac{\text{rect. } AH}{\text{rect. } AC} = \frac{AK}{AB}, \qquad \text{Case 1}$$

Suppose the number of parts into which AB is divided to be continually increased, the length of each part will become less and less, and the point K will approach nearer and nearer to E.

The limit of AK will be AE, and the limit of rect. AH will be rect. AF.

$$\therefore \text{the limit of } \frac{AK}{AB} \text{ will be } \frac{AE}{AB},$$

$$\text{and the limit of } \frac{\text{rect. } AH}{\text{rect. } AC} \text{ will be } \frac{\text{rect. } AF}{\text{rect. } AC}.$$

Now the variables $\frac{AK}{AB}$ and $\frac{\text{rect. } AH}{\text{rect. } AC}$ are always equal however near they approach their limits;

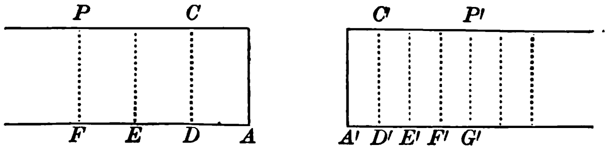
$$\therefore \text{their limits are equal, namely, } \frac{\text{rect. } AF}{\text{rect. } AC} = \frac{AE}{AB}, \qquad \S\ 199$$

Q. E. D.

314. COROLLARY. Two rectangles having equal bases are to each other as their altitudes. By considering the bases of these two rectangles AD and AD, the altitudes will be AB and AE. But we have just shown that these two rectangles are to each other as AB is to AE. Hence two rectangles, with the same base, or equal bases, are to each other as their altitudes.

ANOTHER DEMONSTRATION.

Let AC and $A'C'$ be two rectangles of equal altitudes.



We are to prove $\frac{\text{rect. } AC}{\text{rect. } A'C'} = \frac{AD}{A'D'}$.

Let b and b', S and S' stand for the bases and areas of these rectangles respectively.

Prolong AD and $A'D'$.

Take AD, DE, EF . . . . m in number and all equal,

and $A'D'$, $D'E'$, $E'F'$, $F'G'$ . . . . n in number and all equal.

Complete the rectangles as in the figure.

Then base $AF = mb$,

and base $A'G' = nb'$;

rect. $AP = mS$,

and rect. $A'P' = nS'$.

Now we can prove by superposition, that if AF be $> A'G'$, rect. AP will be $>$ rect. $A'P'$; and if equal, equal; and if less, less.

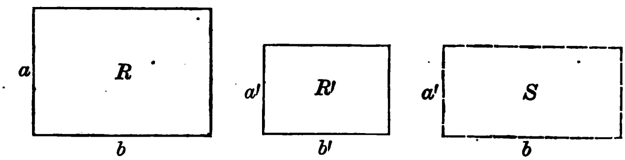
That is, if mb be $> nb'$, mS is $> nS'$; and if equal, equal; and if less, less.

Hence, $b : b' :: S : S'$, Euclid's Def., § 272

Q. E. D.

PROPOSITION II. THEOREM.

315. *Two rectangles are to each other as the products of their bases by their altitudes.*



Let R and R' be two rectangles, having for their bases b and b', and for their altitudes a and a'.

We are to prove $\dfrac{R}{R'} = \dfrac{a \times b}{a' \times b'}$.

Construct the rectangle S, with its base the same as that of R and its altitude the same as that of R'.

Then $\dfrac{R}{S} = \dfrac{a}{a'}$, § 314

(rectangles having the same base are to each other as their altitudes);

and $\dfrac{S}{R'} = \dfrac{b}{b'}$, § 313

(rectangles having the same altitude are to each other as their bases).

By multiplying these two equalities together

$$\frac{R}{R'} = \frac{a \times b}{a' \times b'}.$$

Q. E. D.

316. DEF. The *Area* of a surface is the ratio of that surface to another surface assumed as the unit of measure.

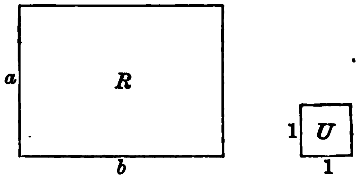
317. DEF. The *Unit of measure* (except the *acre*) is a square a side of which is some linear unit; as a square inch, etc.

318. DEF. Equivalent figures are figures which have equal areas.

REM. In comparing the areas of equivalent figures the symbol (=) is to be read "equal in area."

PROPOSITION III. THEOREM.

319. *The area of a rectangle is equal to the product of its base and altitude.*



Let R be the rectangle, b the base, and a the altitude; and let U be a square whose side is the linear unit.

We are to prove *the area of $R = a \times b$.*

$$\frac{R}{U} = \frac{a \times b}{1 \times 1}, \qquad \S\ 315$$

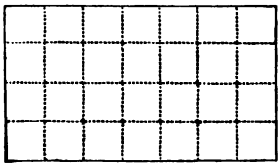
(*two rectangles are to each other as the product of their bases and altitudes*).

But $\frac{R}{U}$ is the area of R, § 316

$\therefore$ the area of $R = a \times b$.

Q. E. D.

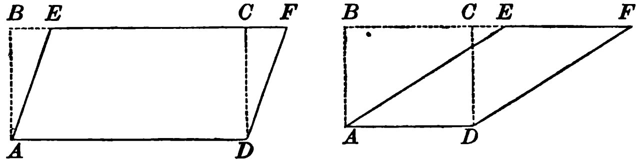
320. SCHOLIUM. When the base and altitude are exactly divisible by the linear unit, this proposition is rendered evident by dividing the figure into squares, each equal to the unit of



measure. Thus, if the base contain seven linear units, and the altitude four, the figure may be divided into twenty-eight squares, each equal to the unit of measure; and the area of the figure equals 7×4.

Proposition IV. Theorem.

321. *The area of a parallelogram is equal to the product of its base and altitude.*



Let $AEFD$ be a parallelogram, AD its base, and CD its altitude.

We are to prove the area of the $\square AEFD = AD \times CD$.

From A draw $AB \parallel$ to DC to meet FE produced.

Then the figure $ABCD$ will be a rectangle, with the same base and altitude as the $\square AEFD$.

In the rt. $\triangle$s ABE and CDF,

$$AB = CD, \qquad \text{§ 126}$$
(*being opposite sides of a rectangle*).

and $$AE = DF, \qquad \text{§ 134}$$
(*being opposite sides of a* $\square$);

$$\therefore \triangle ABE = \triangle CDF, \qquad \text{§ 109}$$
(*two rt.* $\triangle$s *are equal, when the hypotenuse and a side of the one are equal respectively to the hypotenuse and a side of the other*).

Take away the $\triangle CDF$ and we have left the rect. $ABCD$.

Take away the $\triangle ABE$ and we have left the $\square AEFD$.

$$\therefore \text{rect. } ABCD = \square AEFD. \qquad \text{Ax. 3}$$

But the area of the rect. $ABCD = AD \times CD$, § 319
(*the area of a rectangle equals the product of its base and altitude*).

$$\therefore \text{the area of the } \square AEFD = AD \times CD. \qquad \text{Ax. 1}$$

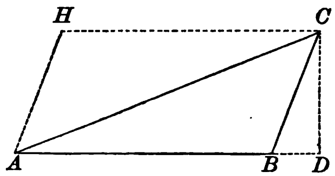
Q. E. D.

322. Corollary 1. Parallelograms having equal bases and equal altitudes are equivalent.

323. Cor. 2. Parallelograms having equal bases are to each other as their altitudes; parallelograms having equal altitudes are to each other as their bases; and any two parallelograms are to each other as the products of their bases by their altitudes.

Proposition V. Theorem.

324. *The area of a triangle is equal to one-half of the product of its base by its altitude.*



Let ABC be a triangle, AB its base, and CD its altitude.

We are to prove *the area of the* $\triangle ABC = \frac{1}{2} AB \times CD$.

From C draw $CH \parallel$ to AB.

From A draw $AH \parallel$ to BC.

The figure $ABCH$ is a parallelogram, § 136
(*having its opposite sides parallel*),

and AC is its diagonal.

$\therefore \triangle ABC = \triangle AHC$, § 133
(*the diagonal of a* $\square$ *divides it into two equal* $\triangle$s).

The area of the $\square$ $ABCH$ is equal to the product of its base by its altitude. § 321

$\therefore$ the area of one-half the $\square$, or the $\triangle ABC$, is equal to one-half the product of its base by its altitude,

or, $\frac{1}{2} AB \times CD$.

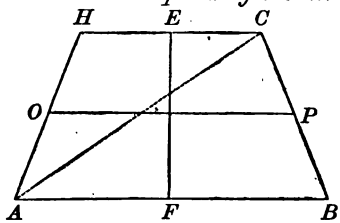
Q. E. D.

325. Corollary 1. Triangles having equal bases and equal altitudes are equivalent.

326. Cor. 2. Triangles having equal bases are to each other as their altitudes; triangles having equal altitudes are to each other as their bases; any two triangles are to each other as the product of their bases by their altitudes.

PROPOSITION VI. THEOREM.

327. *The area of a trapezoid is equal to one-half the sum of the parallel sides multiplied by the altitude.*



Let $ABCH$ be a trapezoid, and EF the altitude.

We are to prove area of $ABCH = \frac{1}{2}(HC + AB)\,EF$.

Draw the diagonal AC.

Then the area of the $\triangle AHC = \frac{1}{2} HC \times EF$, § 324

(*the area of a $\triangle$ is equal to one-half of the product of its base by its altitude*),

and the area of the $\triangle ABC = \frac{1}{2} AB \times EF$, § 324

$\therefore \triangle AHC + \triangle ABC$,

or, area of $ABCH = \frac{1}{2}(HC + AB)\,EF$.

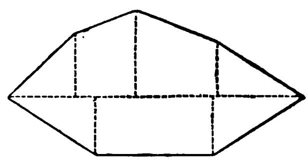
Q. E. D.

328. COROLLARY. The area of a trapezoid is equal to the product of the line joining the middle points of the non-parallel sides multiplied by the altitude; for the line OP, joining the middle points of the non-parallel sides, is equal to $\frac{1}{2}(HC + AB)$. § 142

$\therefore$ by substituting OP for $\frac{1}{2}(HC + AB)$, we have,

the area of $ABCH = OP \times EF$.

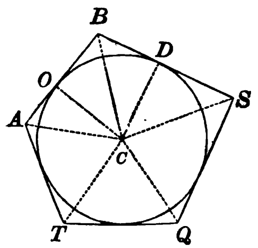
329. SCHOLIUM. The area of an irregular polygon may be found by dividing the polygon into triangles, and by finding the area of each of these triangles separately. But the method generally employed in practice is to draw the longest diagonal, and to let fall perpendiculars upon this diagonal from the other angular points of the polygon.



The polygon is thus divided into figures which are right triangles, rectangles, or trapezoids; and the areas of each of these figures may be readily found.

PROPOSITION VII. THEOREM.

330. *The area of a circumscribed polygon is equal to one-half the product of the perimeter by the radius of the inscribed circle.*



Let $ABSQ$, etc., be a circumscribed polygon, and C the centre of the inscribed circle.

Denote the perimeter of the polygon by P, and the radius of the inscribed circle by R.

We are to prove

the area of the circumscribed polygon $= \frac{1}{2} P \times R$.

Draw CA, CB, CS, etc.;

also draw CO, CD, etc., $\perp$ to AB, BS, etc.

The area of the $\triangle\ CAB = \frac{1}{2} AB \times CO$, § 324

(*the area of a $\triangle$ is equal to one-half the product of its base and altitude*).

The area of the $\triangle\ CBS = \frac{1}{2} BS \times CD$, § 324

$\therefore$ the area of the sum of all the $\triangle$s CAB, CBS, etc.,
$= \frac{1}{2}(AB + BS$, etc.$)\ CO$, § 187

(*for CO, CD, etc., are equal, being radii of the same* $\odot$).

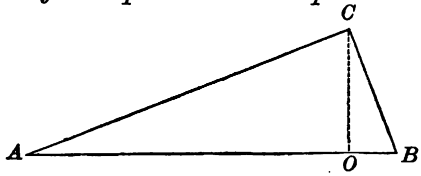
Substitute for $AB + BS + SQ$, etc., P, and for CO, R;

then the area of the circumscribed polygon $= \frac{1}{2} P \times R$.

Q. E. D.

PROPOSITION VIII. THEOREM.

331. *The sum of the squares described on the two sides of a right triangle is equivalent to the square described on the hypotenuse.*



Let ABC be a right triangle with its right angle at C.

We are to prove $\overline{AC}^2 + \overline{CB}^2 = \overline{AB}^2$

Draw $CO \perp$ to AB.

Then $\overline{AC}^2 = AO \times AB$, § 289

(*the square on a side of a rt. $\triangle$ is equal to the product of the hypotenuse by the adjacent segment made by the $\perp$ let fall from the vertex of the rt. $\angle$*);

and $\overline{BC}^2 = BO \times AB$, § 289

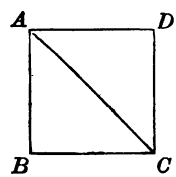
By adding, $\overline{AC}^2 + \overline{BC}^2 = (AO + BO)\,AB$,

$= AB \times AB$,

$= \overline{AB}^2$.

Q. E. D.

332. COROLLARY. The side and diagonal of a square are incommensurable.



Let $ABCD$ be a square, and AC the diagonal.

Then $\overline{AB}^2 + \overline{BC}^2 = \overline{AC}^2$.

or, $2\,\overline{AB}^2 = \overline{AC}^2$.

Divide both sides of the equation by $\overline{AB}^2$,

$$\frac{\overline{AC}^2}{\overline{AB}^2} = 2.$$

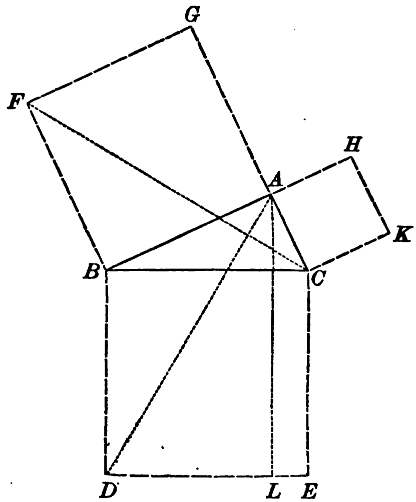
Extract the square root of both sides the equation,

then $$\frac{AC}{AB} = \sqrt{2}.$$

Since the square root of 2 is a number which cannot be exactly found, it follows that the diagonal and side of a square are two incommensurable lines.

Another Demonstration.

333. *The square described on the hypotenuse of a right triangle is equivalent to the sum of the squares on the other two sides.*



Let ABC be a right $\triangle$, having the right angle BAC.

We are to prove $\overline{BC}^2 = \overline{BA}^2 + \overline{AC}^2$.

On BC, CA, AB construct the squares BE, CH, AF.

Through A draw $AL \parallel$ to CE.

Draw AD and FC.

	$\angle BAC$ is a rt. $\angle$,	Hyp.
and	$\angle BAG$ is a rt. $\angle$,	Cons.
	$\therefore CAG$ is a straight line.	
Also	$\angle CAH$ is a rt. $\angle$,	Cons.
	$\therefore BAH$ is a straight line.	
Now	$\angle DBC = \angle FBA$, *(each being a rt. $\angle$).*	Cons.

Add to each the $\angle ABC$;

then $\angle ABD = \angle FBC$,

$\therefore \triangle ABD = \triangle FBC$. § 106

Now $\square BL$ is double $\triangle ABD$,

(being on the same base BD, and between the same ‖s, AL and BD),

and square AF is double $\triangle FBC$,

(being on the same base FB, and between the same ‖s, FB and GC);

$\therefore \square BL =$ square AF.

In like manner, by joining AE and BK, it may be proved that

$\square CL =$ square CH.

Now the square on $BC = \square BL + \square CL$,

$=$ square $AF +$ square CH,

$$\therefore \overline{BC}^2 = \overline{BA}^2 + \overline{AC}^2.$$

Q. E. D.

On Projection.

334. Def. *The Projection of a Point* upon a straight line of indefinite length is the foot of the perpendicular let fall from the point upon the line. Thus, the projection of the point C upon the line AB is the point P.

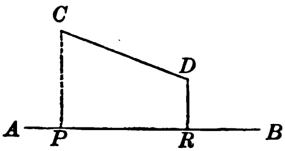


Fig. 1.

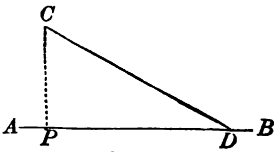


Fig. 2.

The Projection of a Finite Straight Line, as CD (Fig. 1), upon a straight line of indefinite length, as AB, is the part of the line AB intercepted between the perpendiculars CP and DR, let fall from the extremities of the line CD.

Thus the projection of the line CD upon the line AB is the line PR.

If one extremity of the line CD (Fig. 2) be in the line AB, the projection of the line CD upon the line AB is the part of the line AB between the point D and the foot of the perpendicular CP; that is, DP.

Proposition IX. Theorem.

335. *In any triangle, the square on the side opposite an acute angle is equivalent to the sum of the squares of the other two sides diminished by twice the product of one of those sides and the projection of the other upon that side.*

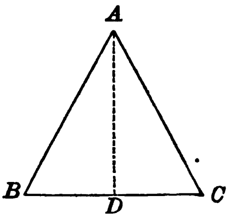


Fig. 1.

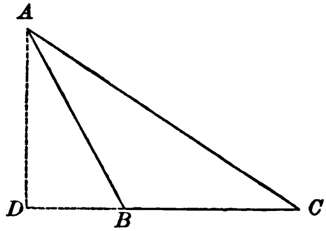


Fig. 2.

Let C be an acute angle of the triangle ABC, and DC the projection of AC upon BC.

We are to prove $\overline{AB}^2 = \overline{BC}^2 + \overline{AC}^2 - 2\,BC \times DC$.

If D fall upon the base (Fig. 1),

$$DB = BC - DC;$$

If D fall upon the base produced (Fig. 2),

$$DB = DC - BC.$$

In either case $\overline{DB}^2 = \overline{BC}^2 + \overline{DC}^2 - 2\,BC \times DC$.

Add $\overline{AD}^2$ to both sides of the equality;

then, $\overline{AD}^2 + \overline{DB}^2 = \overline{BC}^2 + \overline{AD}^2 + \overline{DC}^2 - 2\,BC \times DC$.

But $\overline{AD}^2 + \overline{DB}^2 = \overline{AB}^2$, § 331

(*the sum of the squares on two sides of a rt.* $\triangle$ *is equivalent to the square on the hypotenuse*);

and $\overline{AD}^2 + \overline{DC}^2 = \overline{AC}^2$, § 331

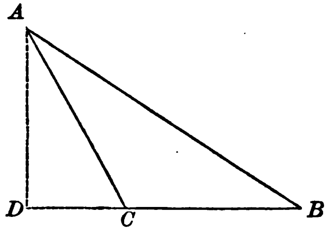
Substitute $\overline{AB}^2$ and $\overline{AC}^2$ for their equivalents in the above equality;

then, $\overline{AB}^2 = \overline{BC}^2 + \overline{AC}^2 - 2\,BC \times DC$.

Q. E. D.

Proposition X. Theorem.

336. *In any obtuse triangle, the square on the side opposite the obtuse angle is equivalent to the sum of the squares of the other two sides increased by twice the product of one of those sides and the projection of the other on that side.*



Let C be the obtuse angle of the triangle ABC, and CD be the projection of AC upon BC produced.

We are to prove $\overline{AB}^2 = \overline{BC}^2 + \overline{AC}^2 + 2\,BC \times DC.$

$$DB = BC + DC.$$

Squaring, $\overline{DB}^2 = \overline{BC}^2 + \overline{DC}^2 + 2\,BC \times DC.$

Add $\overline{AD}^2$ to both sides of the equality;

then, $\overline{AD}^2 + \overline{DB}^2 = \overline{BC}^2 + \overline{AD}^2 + \overline{DC}^2 + 2\,BC \times DC.$

But $\overline{AD}^2 + \overline{DB}^2 = \overline{AB}^2,$ § 331

(*the sum of the squares on two sides of a rt.* $\triangle$ *is equivalent to the square on the hypotenuse*);

and $\overline{AD}^2 + \overline{DC}^2 = \overline{AC}^2.$ § 331

Substitute $\overline{AB}^2$ and $\overline{AC}^2$ for their equivalents in the above equality;

then, $\overline{AB}^2 = \overline{BC}^2 + \overline{AC}^2 + 2\,BC \times DC.$

Q. E. D.

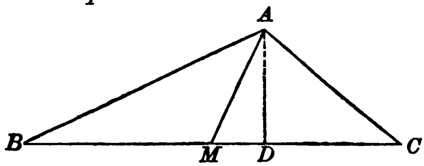
337. Definition. A *Medial* line of a triangle is a straight line drawn from any vertex of the triangle to the middle point of the opposite side.

PROPOSITION XI. THEOREM.

338. *In any triangle, if a medial line be drawn from the vertex to the base:*

I. *The sum of the squares on the two sides is equivalent to twice the square on half the base, increased by twice the square on the medial line;*

II. *The difference of the squares on the two sides is equivalent to twice the product of the base by the projection of the medial line upon the base.*



In the triangle ABC let AM be the medial line and MD the projection of AM upon the base BC. Also let AB be greater than AC.

We are to prove

$$\text{I.}\quad \overline{AB}^2 + \overline{AC}^2 = 2\,\overline{BM}^2 + 2\,\overline{AM}^2.$$

$$\text{II.}\quad \overline{AB}^2 - \overline{AC}^2 = 2\,BC \times MD.$$

Since $AB > AC$, the $\angle AMB$ will be obtuse and the $\angle AMC$ will be acute. § 116

Then $\overline{AB}^2 = \overline{BM}^2 + \overline{AM}^2 + 2\,BM \times MD$, § 336

(*in any obtuse $\triangle$ the square on the side opposite the obtuse $\angle$ is equivalent to the sum of the squares on the other two sides increased by twice the product of one of those sides and the projection of the other on that side*);

and $\overline{AC}^2 = \overline{MC}^2 + \overline{AM}^2 - 2\,MC \times MD$, § 335

(*in any $\triangle$ the square on the side opposite an acute $\angle$ is equivalent to the sum of the squares on the other two sides, diminished by twice the product of one of those sides and the projection of the other upon that side*).

Add these two equalities, and observe that $BM = MC$.

Then $\overline{AB}^2 + \overline{AC}^2 = 2\,\overline{BM}^2 + 2\,\overline{AM}^2$.

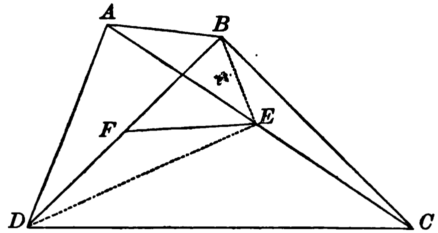
Subtract the second equality from the first.

Then $\overline{AB}^2 - \overline{AC}^2 = 2\,BC \times MD$.

Q. E. D.

PROPOSITION XII. THEOREM.

339. *The sum of the squares on the four sides of any quadrilateral is equivalent to the sum of the squares on the diagonals together with four times the square of the line joining the middle points of the diagonals.*



In the quadrilateral $ABCD$, let the diagonals be AC and BD, and FE the line joining the middle points of the diagonals.

We are to prove

$$\overline{AB}^2 + \overline{BC}^2 + \overline{CD}^2 + \overline{DA}^2 = \overline{AC}^2 + \overline{BD}^2 + 4\,\overline{EF}^2.$$

Draw BE and DE.

Now $\overline{AB}^2 + \overline{BC}^2 = 2\left(\frac{AC}{2}\right)^2 + 2\,\overline{BE}^2$, § 338

(the sum of the squares on the two sides of a $\triangle$ is equivalent to twice the square on half the base increased by twice the square on the medial line to the base),

and $\overline{CD}^2 + \overline{DA}^2 = 2\left(\frac{AC}{2}\right)^2 + 2\,\overline{DE}^2.$ § 338

Adding these two equalities,

$$\overline{AB}^2 + \overline{BC}^2 + \overline{CD}^2 + \overline{DA}^2 = 4\left(\frac{AC}{2}\right)^2 + 2\,(\overline{BE}^2 + \overline{DE}^2).$$

But $\overline{BE}^2 + \overline{DE}^2 = 2\left(\frac{BD}{2}\right)^2 + 2\,\overline{EF}^2,$ § 338

(the sum of the squares on the two sides of a $\triangle$ is equivalent to twice the square on half the base increased by twice the square on the medial line to the base).

Substitute in the above equality for $(\overline{BE}^2 + \overline{DE}^2)$ its equivalent;

then $\overline{AB}^2 + \overline{BC}^2 + \overline{CD}^2 + \overline{DA}^2 = 4\left(\frac{AC}{2}\right)^2 + 4\left(\frac{BD}{2}\right)^2 + 4\,\overline{EF}^2$

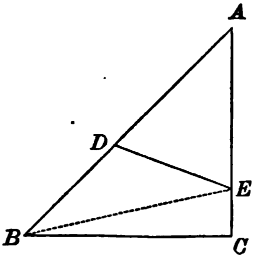
$$= \overline{AC}^2 + \overline{BD}^2 + 4\,\overline{EF}^2$$

Q. E. D.

340. COROLLARY. The sum of the squares on the four sides of a parallelogram is equivalent to the sum of the squares on the diagonals.

Proposition XIII. Theorem.

341. *Two triangles having an angle of the one equal to an angle of the other are to each other as the products of the sides including the equal angles.*



Let the triangles ABC and ADE have the common angle A.

We are to prove $$\frac{\triangle ABC}{\triangle ADE} = \frac{AB \times AC}{AD \times AE}.$$

Draw BE.

Now $$\frac{\triangle ABC}{\triangle ABE} = \frac{AC}{AE},$$ § 326

(*$\triangle$ having the same altitude are to each other as their bases*).

Also $$\frac{\triangle ABE}{\triangle ADE} = \frac{AB}{AD},$$ § 326

(*$\triangle$ having the same altitude are to each other as their bases*).

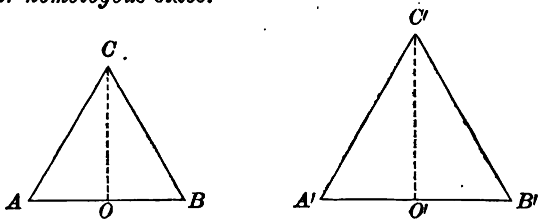
Multiply these equalities;

then $$\frac{\triangle ABC}{\triangle ADE} = \frac{AB \times AC}{AD \times AE}.$$

Q. E. D.

PROPOSITION XIV. THEOREM.

342. *Similar triangles are to each other as the squares on their homologous sides.*



Let the two triangles be ACB and $A'C'B'$.

We are to prove $\dfrac{\triangle ACB}{\triangle A'C'B'} = \dfrac{\overline{AB}^2}{\overline{A'B'}^2}$.

Draw the perpendiculars CO and $C'O'$.

Then $\dfrac{\triangle ACB}{\triangle A'C'B'} = \dfrac{AB \times CO}{A'B' \times C'O'} = \dfrac{AB}{A'B'} \times \dfrac{CO}{C'O'}$, § 326

(*two* △ *are to each other as the products of their bases by their altitudes*).

But $\dfrac{AB}{A'B'} = \dfrac{CO}{C'O'}$, § 297

(*the homologous altitudes of similar* △ *have the same ratio as their homologous bases*).

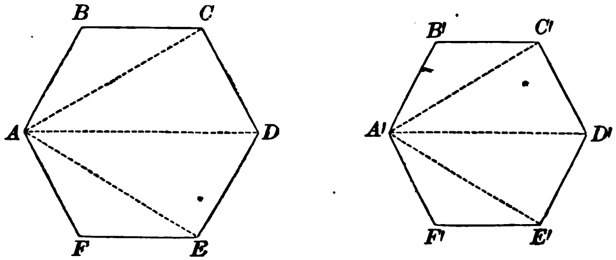
Substitute, in the above equality, for $\dfrac{CO}{C'O'}$ its equal $\dfrac{AB}{A'B'}$;

then $\dfrac{\triangle ACB}{\triangle A'C'B'} = \dfrac{AB}{A'B'} \times \dfrac{AB}{A'B'} = \dfrac{\overline{AB}^2}{\overline{A'B'}^2}$.

Q. E. D.

Proposition XV. Theorem.

343. *Two similar polygons are to each other as the squares on any two homologous sides.*



Let the two similar polygons be** $A\ B\ C$, **etc., and** $A'\ B'\ C'$, **etc.

We are to prove $\dfrac{A\ B\ C, \text{ etc.}}{A'\ B'\ C', \text{ etc.}} = \dfrac{\overline{A\ B}^2}{\overline{A'\ B'}^2}.$

From the homologous vertices A and A' draw diagonals.

Now $\dfrac{A\ B}{A'\ B'} = \dfrac{B\ C}{B'\ C'} = \dfrac{C\ D}{C'\ D'}$, etc.,

(similar polygons have their homologous sides proportional);

$\therefore$ by squaring, $\dfrac{\overline{A\ B}^2}{\overline{A'\ B'}^2} = \dfrac{\overline{B\ C}^2}{\overline{B'\ C'}^2} = \dfrac{\overline{C\ D}^2}{\overline{C'\ D'}^2}$, etc.

The $\triangle$s $A\ B\ C$, $A\ C\ D$, etc., are respectively similar to $A'\ B'\ C'$, $A'\ C'\ D'$, etc., § 294

(two similar polygons are composed of the same number of $\triangle$s similar to each other and similarly placed).

$$\therefore \frac{\triangle\ A\ B\ C}{\triangle\ A'\ B'\ C'} = \frac{\overline{A\ B}^2}{\overline{A'\ B'}^2}, \qquad \text{§ 342}$$

(similar $\triangle$s are to each other as the squares on their homologous sides),

and $$\frac{\triangle\ A\ C\ D}{\triangle\ A'\ C'\ D'} = \frac{\overline{C\ D}^2}{\overline{C'\ D'}^2}. \qquad \text{§ 342}$$

But $$\frac{\overline{CD}^2}{\overline{C'D'}^2} = \frac{\overline{AB}^2}{\overline{A'B'}^2},$$

$$\therefore \frac{\triangle ABC}{\triangle A'B'C'} = \frac{\triangle ACD}{\triangle A'C'D'}.$$

In like manner we may prove that the ratio of any two of the similar $\triangle$ is the same as that of any other two.

$$\therefore \frac{\triangle ABC}{\triangle A'B'C'} = \frac{\triangle ACD}{\triangle A'C'D'} = \frac{\triangle ADE}{\triangle A'D'E'} = \frac{\triangle AEF}{\triangle A'E'F'},$$

$$\therefore \frac{\triangle ABC + ACD + ADE + AEF}{\triangle A'B'C' + A'C'D' + A'D'E' + A'E'F'} = \frac{\triangle ABC}{\triangle A'B'C'},$$

(in a series of equal ratios the sum of the antecedents is to the sum of the consequents as any antecedent is to its consequent).

But $$\frac{\triangle ABC}{\triangle A'B'C'} = \frac{\overline{AB}^2}{\overline{A'B'}^2}, \qquad \S\ 342$$

(similar $\triangle$ are to each other as the squares on their homologous sides);

$$\therefore \frac{\text{the polygon } ABC\text{, etc.}}{\text{the polygon } A'B'C'\text{, etc.}} = \frac{\overline{AB}^2}{\overline{A'B'}^2}.$$

Q. E. D.

344. Corollary 1. Similar polygons are to each other as the squares on any two homologous lines.

345. Cor. 2. The homologous sides of two similar polygons have the same ratio as the square roots of their areas.

Let S and S' represent the areas of the two similar polygons ABC, etc., and $A'B'C'$, etc., respectively.

Then $$S : S' :: \overline{AB}^2 : \overline{A'B'}^2,$$

(similar polygons are to each other as the squares of their homologous sides).

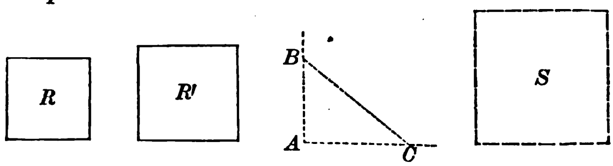
$$\therefore \sqrt{S} : \sqrt{S'} :: AB : A'B', \qquad \S\ 268$$

or, $$AB : A'B' :: \sqrt{S} : \sqrt{S'}.$$

On Constructions.

Proposition XVI. Problem.

346. *To construct a square equivalent to the sum of two given squares.*



Let R and R' be two given squares.

It is required to construct a square $= R + R'$.

Construct the rt. $\angle A$.

Take AB equal to a side of R,

and AC equal to a side of R'.

Draw BC.

Then BC will be a side of the square required.

For $\overline{BC}^2 = \overline{AB}^2 + \overline{AC}^2$, § 331

(the square on the hypotenuse of a rt. $\triangle$ is equivalent to the sum of the squares on the two sides).

Construct the square S, having each of its sides equal to BC.

Substitute for $\overline{BC}^2$, $\overline{AB}^2$ and $\overline{AC}^2$, S, R, and R' respectively;

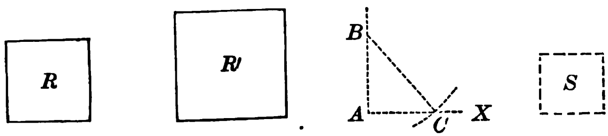
then $S = R + R'$.

$\therefore$ S is the square required.

Q. E. F.

PROPOSITION XVII PROBLEM.

347. *To construct a square equivalent to the difference of two given squares.*



Let R be the smaller square and R' the larger.

It is required to construct a square $= R' - R$.

Construct the rt. $\angle A$.

Take AB equal to a side of R.

From B as a centre, with a radius equal to a side of R',

describe an arc cutting the line AX at C.

Then AC will be a side of the square required.

For draw BC.

$$\overline{AB}^2 + \overline{AC}^2 = \overline{BC}^2, \qquad \S\ 331$$

(*the sum of the squares on the two sides of a rt.* $\triangle$ *is equivalent to the square on the hypotenuse*).

By transposing, $\overline{AC}^2 = \overline{BC}^2 - \overline{AB}^2$.

Construct the square S, having each of its sides equal to AC.

Substitute for $\overline{AC}^2$, $\overline{BC}^2$, and $\overline{AB}^2$, S, R', and R respectively;

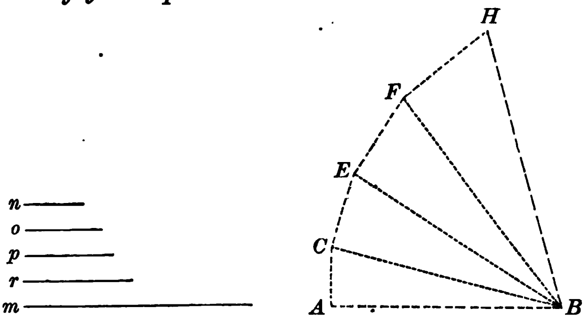
then $S = R' - R$.

$\therefore S$ is the square required.

Q. E. F.

Proposition XVIII. Problem.

348. *To construct a square equivalent to the sum of any number of given squares.*



Let m, n, o, p, r be sides of the given squares.

It is required to construct a square $= m^2 + n^2 + o^2 + p^2 + r^2$.

Take $AB = m$.

Draw $AC = n$ and $\perp$ to AB at A.

Draw BC.

Draw $CE = o$ and $\perp$ to BC at C, and draw BE.

Draw $EF = p$ and $\perp$ to BE at E, and draw BF.

Draw $FH = r$ and $\perp$ to BF at F, and draw BH.

The square constructed on BH is the square required.

For $\overline{BH}^2 = \overline{FH}^2 + \overline{BF}^2$,

$= \overline{FH}^2 + \overline{EF}^2 + \overline{EB}^2$,

$= \overline{FH}^2 + \overline{EF}^2 + \overline{EC}^2 + \overline{CB}^2$,

$= \overline{FH}^2 + \overline{EF}^2 + \overline{EC}^2 + \overline{CA}^2 + \overline{AB}^2$, § 331

(*the sum of the squares on two sides of a rt.* $\triangle$ *is equivalent to the square on the hypotenuse*).

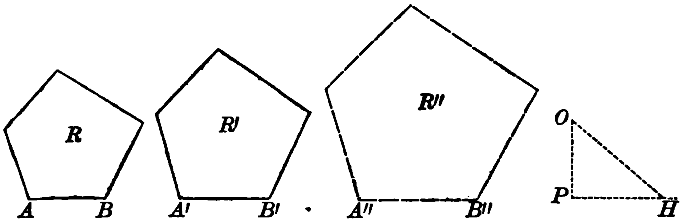
Substitute for AB, CA, EC, EF, and FH, m, n, o, p, and r respectively;

then $\overline{BH}^2 = m^2 + n^2 + o^2 + p^2 + r^2$.

Q. E. F.

PROPOSITION XIX. PROBLEM.

349. *To construct a polygon similar to two given similar polygons and equivalent to their sum.*



Let R and R' be two similar polygons, and AB and $A'B'$ two homologous sides.

It is required to construct a similar polygon equivalent to $R + R'$.

Construct the rt. $\angle P$.

Take $PH = A'B'$, and $PO = AB$.

Draw OH.

Take $A''B'' = OH$.

Upon $A''B''$, homologous to AB, construct the polygon R'' similar to R.

Then R'' is the polygon required.

For $R' : R :: \overline{A'B'}^2 : \overline{AB}^2$, § 343

(*similar polygons are to each other as the squares on their homologous sides*).

Also $R'' : R' :: \overline{A''B''}^2 : \overline{A'B'}^2$. § 343

In the first proportion, by composition,

$$R' + R : R' :: \overline{A'B'}^2 + \overline{AB}^2 : \overline{A'B'}^2, \quad \S\ 264$$

$$:: \overline{PH}^2 + \overline{PO}^2 : \overline{PH}^2,$$

$$:: \overline{HO}^2 : \overline{PH}^2.$$

But $R'' : R' :: \overline{A''B''}^2 : \overline{A'B'}^2$,

$$:: \overline{HO}^2 : \overline{PH}^2.$$

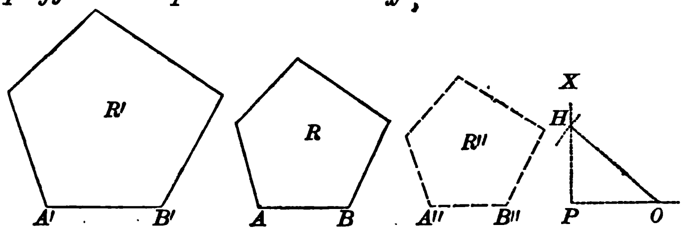
$$\therefore R'' : R' :: R' + R : R';$$

$$\therefore R'' = R' + R.$$

Q. E. F

PROPOSITION XX. PROBLEM.

350. *To construct a polygon similar to two given similar polygons and equivalent to their difference.*



Let R and R' be two similar polygons, and AB and $A'B'$ two homologous sides.

It is required to construct a similar polygon which shall be equivalent to $R' - R$.

Construct the rt. $\angle P$,

and take $PO = AB$.

From O as a centre, with a radius equal to $A'B'$,

describe an arc cutting PX at H.

Draw OH.

Take $A''B'' = PH$.

On $A''B''$, homologous to AB, construct the polygon R'' similar to R.

Then R'' is the polygon required.

For $R' : R :: \overline{A'B'}^2 : \overline{AB}^2$, § 343

(*similar polygons are to each other as the squares on their homologous sides*).

Also $R'' : R :: \overline{A''B''}^2 : \overline{AB}^2$. § 343

In the first proportion, by division,

$$R' - R : R :: \overline{A'B'}^2 - \overline{AB}^2 : \overline{AB}^2, \quad \S\ 265$$

$$:: \overline{OH}^2 - \overline{OP}^2 : \overline{OP}^2,$$

$$:: \overline{PH}^2 : \overline{OP}^2.$$

But $R'' : R :: \overline{A''B''}^2 : \overline{AB}^2$,

$$:: \overline{PH}^2 : \overline{OP}^2.$$

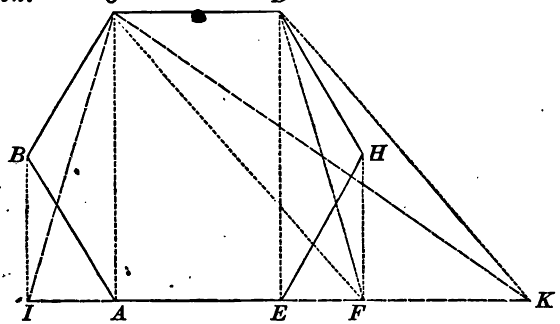
$$\therefore R'' : R :: R' - R : R;$$

$$\therefore R'' = R' - R.$$

Q. E. F.

Proposition XXI. Problem.

351. *To construct a triangle equivalent to a given polygon.*



Let $A\,B\,C\,D\,H\,E$ be the given polygon.

It is required to construct a triangle equivalent to the given polygon.

From D draw $D\,E$, and from H draw $H\,F$ ∥ to $D\,E$.

Produce $A\,E$ to meet $H\,F$ at F, and draw $D\,F$.

The polygon $A\,B\,C\,D\,F$ has one side less than the polygon $A\,B\,C\,D\,H\,E$, but the two are equivalent.

For the part $A\,B\,C\,D\,E$ is common,

and the $\triangle\ D\,E\,F = \triangle\ D\,E\,H$, for the base $D\,E$ is common, and their vertices F and H are in the line $F\,H$ ∥ to the base, § 325

(*△ having the same base and equal altitudes are equivalent*).

Again, draw $C\,F$, and draw $D\,K$ ∥ to $C\,F$ to meet $A\,F$ produced at K.

Draw $C\,K$.

The polygon $A\,B\,C\,K$ has one side less than the polygon $A\,B\,C\,D\,F$, but the two are equivalent.

For the part $A\,B\,C\,F$ is common,

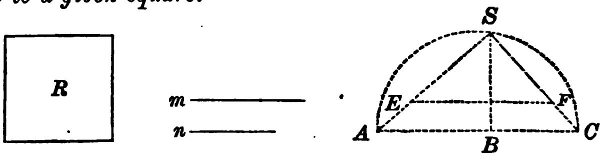
and the $\triangle\ C\,F\,K = \triangle\ C\,F\,D$, for the base $C\,F$ is common, and their vertices K and D are in the line $K\,D$ ∥ to the base. § 325

In like manner we may continue to reduce the number of sides of the polygon until we obtain the $\triangle\ C\,I\,K$.

Q. E. F.

Proposition XXII. Problem.

352. *To construct a square which shall have a given ratio to a given square.*



Let R be the given square, and $\frac{n}{m}$ the given ratio.

It is required to construct a square which shall be to R as n is to m.

On a straight line take $AB = m$, and $BC = n$.

On AC as a diameter, describe a semicircle.

At B erect the $\perp BS$, and draw SA and SC.

Then the $\triangle ASC$ is a rt. $\triangle$ with the rt. $\angle$ at S, § 204

(being inscribed in a semicircle.)

On SA, or SA produced, take SE equal to a side of R.

Draw $EF \parallel$ to AC.

Then SF is a side of the square required.

For $$\frac{\overline{SA}^2}{\overline{SC}^2} = \frac{AB}{BC}, \qquad \text{§ 289}$$

(the squares on the sides of a rt. $\triangle$ have the same ratio as the segments of the hypotenuse made by the $\perp$ let fall from the vertex of the rt. $\angle$).

Also $$\frac{SA}{SC} = \frac{SE}{SF}, \qquad \text{§ 275}$$

(a straight line drawn through two sides of a $\triangle$, parallel to the third side, divides those sides proportionally).

Square the last equality;

then $$\frac{\overline{SA}^2}{\overline{SC}^2} = \frac{\overline{SE}^2}{\overline{SF}^2}.$$

Substitute, in the first equality, for $\frac{\overline{SA}^2}{\overline{SC}^2}$ its equal $\frac{\overline{SE}^2}{\overline{SF}^2}$;

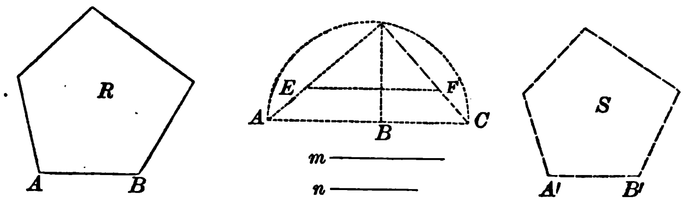
then $$\frac{\overline{SE}^2}{\overline{SF}^2} = \frac{AB}{BC} = \frac{m}{n},$$

that is, the square having a side equal to SF will have the same ratio to the square R, as n has to m.

Q. E. F.

Proposition XXIII. Problem.

353. *To construct a polygon similar to a given polygon and having a given ratio to it.*



Let R be the given polygon and $\frac{n}{m}$ the given ratio.

It is required to construct a polygon similar to R, which shall be to R as n is to m.

Find a line, $A'B'$, such that the square constructed upon it shall be to the square constructed upon AB as n is to m. § 352

Upon $A'B'$ as a side homologous to AB, construct the polygon S similar to R.

Then S is the polygon required.

For $$\frac{S}{R} = \frac{\overline{A'B'}^2}{\overline{AB}^2},$$ § 343

(*similar polygons are to each other as the squares on their homologous sides*).

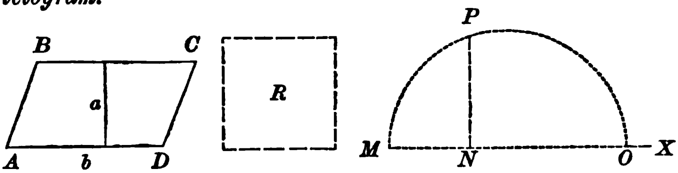
But $$\frac{\overline{A'B'}^2}{\overline{AB}^2} = \frac{n}{m};$$ Cons.

$$\therefore \frac{S}{R} = \frac{n}{m}, \quad \text{or,} \quad S : R :: n : m.$$

Q. E. F.

PROPOSITION XXIV. PROBLEM.

354. *To construct a square equivalent to a given parallelogram.*



Let ABCD be a parallelogram, b its base, and a its altitude.

It is required to construct a square = ▱ ABCD.

Upon the line MX take $MN = a$, and $NO = b$.

Upon MO as a diameter, describe a semicircle.

At N erect $NP \perp$ to MO.

Then the square R, constructed upon a line equal to NP, is equivalent to the ▱ $ABCD$.

For $MN : NP :: NP : NO$, § 307

(a ⊥ let fall from any point of a circumference to the diameter is a mean proportional between the segments of the diameter).

$\therefore \overline{NP}^2 = MN \times NO = a \times b$, § 259

(the product of the means is equal to the product of the extremes).

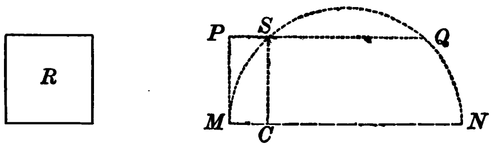
Q. E. F.

355. COROLLARY 1. A square may be constructed equivalent to a triangle, by taking for its side a mean proportional between the base and one-half the altitude of the triangle.

356. COR. 2. A square may be constructed equivalent to any polygon, by first reducing the polygon to an equivalent triangle, and then constructing a square equivalent to the triangle.

PROPOSITION XXV. PROBLEM.

357. *To construct a parallelogram equivalent to a given square, and having the sum of its base and altitude equal to a given line.*



Let R be the given square, and let the sum of the base and altitude of the required parallelogram be equal to the given line MN.

It is required to construct a $\square = R$, and having the sum of its base and altitude $= MN$.

Upon MN as a diameter, describe a semicircle.

At M erect a $\perp$ MP, equal to a side of the given square R.

Draw $PQ \parallel$ to MN, cutting the circumference at S.

Draw $SC \perp$ to MN.

Any $\square$ having CM for its altitude and CN for its base, is equivalent to R.

For SC is $\parallel$ to PM, § 65
(two straight lines $\perp$ to the same straight line are $\parallel$).

$\therefore SC = PM$, § 135
($\parallel$s comprehended between $\parallel$s are equal).

$$\therefore \overline{SC}^2 = \overline{PM}^2 = R.$$

But $MC : SC :: SC : CN$, § 307
(a $\perp$ let fall from any point in a circumference to the diameter is a mean proportional between the segments of the diameter).

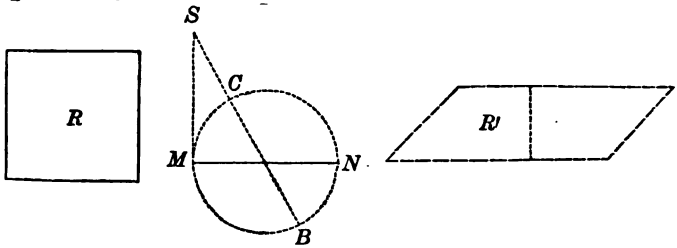
Then $\overline{SC}^2 = MC \times CN$, § 259
(the product of the means is equal to the product of the extremes).

Q. E. F.

358. SCHOLIUM. The problem is impossible when the side of the square is greater than one-half the line MN.

Proposition XXVI. Problem.

359. *To construct a parallelogram equivalent to a given square, and having the difference of its base and altitude equal to a given line.*



Let R be the given square, and let the difference of the base and altitude of the required parallelogram be equal to the given line MN.

It is required to construct a ▱ = *R, with the difference of the base and altitude* = *MN.*

Upon the given line MN as a diameter, describe a circle.

From M draw MS, tangent to the ⊙, and equal to a side of the given square R.

Through the centre of the ⊙, draw SB intersecting the circumference at C and B.

Then any ▱, as R', having SB for its base and SC for its altitude, is equivalent to R.

For $$SB : SM :: SM : SC, \qquad \S\ 292$$
(*if from a point without a ⊙, a secant and a tangent be drawn, the tangent is a mean proportional between the whole secant and the part without the* ⊙).

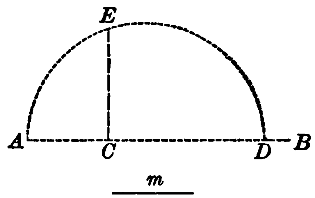
Then $$\overline{SM}^2 = SB \times SC; \qquad \S\ 259$$

and the difference between SB and SC is the diameter of the ⊙, that is, MN.

Q. E. F.

Proposition XXVII. Problem.

360. *Given $x = \sqrt{2}$, to construct x.*



Let m represent the unit of length.

It is required to find a line which shall represent the square root of 2.

On the indefinite line AB, take $AC = m$, and $CD = 2\,m$.

On AD as a diameter describe a semi-circumference.

At C erect a $\perp$ to AB, intersecting the circumference at E.

Then CE is the line required.

For $AC : CE :: CE : CD$, § 307

(the $\perp$ let fall from any point in the circumference to the diameter, is a mean proportional between the segments of the diameter);

$$\therefore \overline{CE}^2 = AC \times CD, \quad \text{§ 259}$$

$$\therefore CE = \sqrt{AC \times CD},$$

$$= \sqrt{1 \times 2} = \sqrt{2}.$$

Q. E. F.

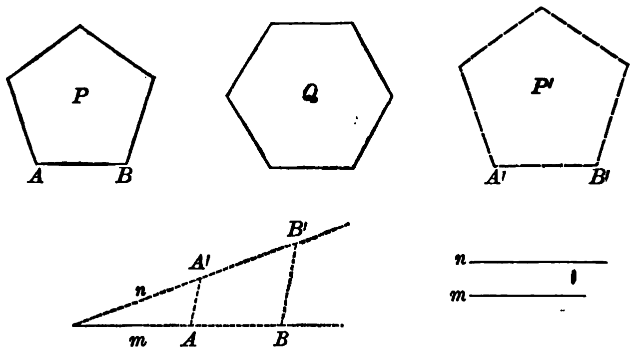
Ex. 1. Given $x = \sqrt{5}$, $y = \sqrt{7}$, $z = 2\sqrt{3}$; to construct x, y, and z.

2. Given $2 : x :: x : 3$; to construct x.

3. Construct a square equivalent to a given hexagon.

PROPOSITION XXVIII. PROBLEM.

361. *To construct a polygon similar to a given polygon P, and equivalent to a given polygon Q.*



Let P and Q be two given polygons, and AB a side of polygon P.

It is required to construct a polygon similar to P and equivalent to Q.

Find a square equivalent to P, § 356

and let m be equal to one of its sides.

Find a square equivalent to Q, § 356

and let n be equal to one of its sides.

Find a fourth proportional to m, n, and AB. § 304

Let this fourth proportional be $A'B'$.

Upon $A'B'$, homologous to AB, construct the polygon P' similar to the given polygon P.

Then P' is the polygon required.

For $\frac{m}{n} = \frac{AB}{A'B'}$. Cons.

Squaring, $\frac{m^2}{n^2} = \frac{\overline{AB}^2}{\overline{A'B'}^2}$.

But $P = m^2$, Cons.

and $Q = n^2$; Cons.

$$\therefore \frac{P}{Q} = \frac{m^2}{n^2} = \frac{\overline{AB}^2}{\overline{A'B'}^2}.$$

But $\frac{P}{P'} = \frac{\overline{AB}^2}{\overline{A'B'}^2}$, § 343

(similar polygons are to each other as the squares on their homologous sides);

$$\therefore \frac{P}{Q} = \frac{P}{P'};$$ Ax. 1

$\therefore$ P' is equivalent to Q, and is similar to P by construction.

Q. E. F.

Ex. 1. Construct a square equivalent to the sum of three given squares whose sides are respectively 2, 3, and 5.

2. Construct a square equivalent to the difference of two given squares whose sides are respectively 7 and 3.

3. Construct a square equivalent to the sum of a given triangle and a given parallelogram.

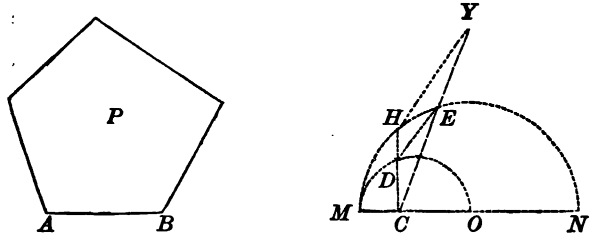
4. Construct a rectangle having the difference of its base and altitude equal to a given line, and its area equivalent to the sum of a given triangle and a given pentagon.

5. Given a hexagon; to construct a similar hexagon whose area shall be to that of the given hexagon as 3 to 2.

6. Construct a pentagon similar to a given pentagon and equivalent to a given trapezoid.

Proposition XXIX. Problem.

362. *To construct a polygon similar to a given polygon, and having two and a half times its area.*



Let P be the given polygon.

It is required to construct a polygon similar to P, and equivalent to $2\frac{1}{2}$ P.

Let AB be a side of the given polygon P.

Then $\sqrt{1} : \sqrt{2\frac{1}{2}} :: AB : x$,

or $\sqrt{2} : \sqrt{5} :: AB : x$, § 345

(the homologous sides of similar polygons are to each other as the square roots of their areas).

Take any convenient unit of length, as MC, and apply it six times to the indefinite line MN.

On MO ($= 3\,MC$) describe a semi-circumference;

and on MN ($= 6\,MC$) describe a semi-circumference.

At C erect a $\perp$ to MN, intersecting the semi-circumferences at D and H.

Then CD is the $\sqrt{2}$, and CH is the $\sqrt{5}$. § 360

Draw CY, making any convenient $\angle$ with CH.

On CY take $CE = AB$.

From D draw DE,

and from H draw $HY \parallel$ to DE.

Then CY will equal x, and be a side of the polygon required, homologous to AB.

For $$CD : CH :: CE : CY,$$ § 275

(a line drawn through two sides of a △, ∥ to the third side, divides the two sides proportionally).

Substitute their equivalents for CD, CH, and CE;

then $$\sqrt{2} : \sqrt{5} :: AB : CY.$$

On CY, homologous to AB, construct a polygon similar to the given polygon P;

and this is the polygon required.

Q. E. F.

Ex. 1. The perpendicular distance between two parallels is 30, and a line is drawn across them at an angle of 45°; what is its length between the parallels?

2. Given an equilateral triangle each of whose sides is 20; find the altitude of the triangle, and its area.

3. Given the angle A of a triangle equal to $\frac{2}{3}$ of a right angle, the angle B equal to $\frac{1}{3}$ of a right angle, and the side a, opposite the angle A, equal to 10; construct the triangle.

4. The two segments of a chord intersected by another chord are 6 and 5, and one segment of the other chord is 3; what is the other segment of the latter chord?

5. If a circle be inscribed in a right triangle: show that the difference between the sum of the two sides containing the right angle and the hypotenuse is equal to the diameter of the circle.

6. Construct a parallelogram the area and perimeter of which shall be respectively equal to the area and perimeter of a given triangle.

7. Given the difference between the diagonal and side of a square; construct the square.

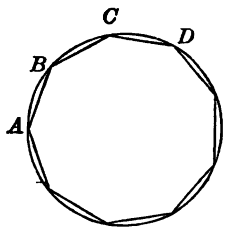
BOOK V.

REGULAR POLYGONS AND CIRCLES.

363. Def. A *Regular Polygon* is a polygon which is equilateral and equiangular.

Proposition I. Theorem.

364. *Every equilateral polygon inscribed in a circle is a regular polygon.*



Let $A B C$, etc., be an equilateral polygon inscribed in a circle.

We are to prove the polygon $A B C$, etc., regular.

The arcs $A B$, $B C$, $C D$, etc., are equal, § 182
(*in the same ⊙, equal chords subtend equal arcs*).

$\therefore$ arcs $A B C$, $B C D$, etc., are equal, Ax. 6

$\therefore$ the $\angle$s A, B, C, etc., are equal,
(*being inscribed in equal segments*).

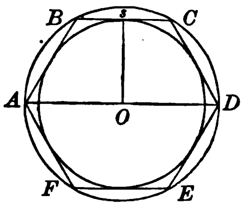
$\therefore$ the polygon $A B C$, etc., is a regular polygon, being equilateral and equiangular.

Q. E. D.

PROPOSITION II. THEOREM.

365. I. *A circle may be circumscribed about a regular polygon.*

II. *A circle may be inscribed in a regular polygon.*



Let A B C D, etc., be a regular polygon.

We are to prove that a ⊙ may be circumscribed about this regular polygon, and also a ⊙ may be inscribed in this regular polygon.

CASE I. — Describe a circumference passing through A, B, and C.

From the centre O, draw OA, OD,

and draw $Os \perp$ to chord BC.

On Os as an axis revolve the quadrilateral $OABs$,

until it comes into the plane of $OsCD$.

The line sB will fall upon sC,

(for $\angle OsB = \angle OsC$, both being rt. $\angle$s).

The point B will fall upon C, § 183

(since $sB = sC$).

The line BA will fall upon CD, § 363

(since $\angle B = \angle C$, being $\angle$s of a regular polygon).

The point A will fall upon D, § 363

(since $BA = CD$, being sides of a regular polygon).

∴ the line OA will coincide with line OD,

(their extremities being the same points).

∴ the circumference will pass through D.

In like manner we may prove that the circumference, passing through vertices B, C, and D will also pass through the vertex E, and thus through all the vertices of the polygon in succession.

CASE II. — The sides of the regular polygon, being equal chords of the circumscribed ⊙, are equally distant from the centre, § 185

∴ a circle described with the centre O and a radius Os will touch all the sides, and be inscribed in the polygon. § 174

Q. E. D.

366. Def. The *Centre* of a regular polygon is the common centre O of the circumscribed and inscribed circles.

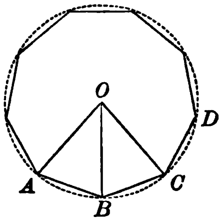
367. Def. The *Radius* of a regular polygon is the radius OA of the circumscribed circle.

368. Def. The *Apothem* of a regular polygon is the radius Os of the inscribed circle.

369. Def. The *Angle at the centre* is the angle included by the radii drawn to the extremities of any side.

Proposition III. Theorem.

370. *Each angle at the centre of a regular polygon is equal to four right angles divided by the number of sides of the polygon.*



Let ABC, etc., be a regular polygon of n sides.

We are to prove $\angle AOB = \dfrac{4 \text{ rt. } \angle s}{n}$.

Circumscribe a $\odot$ about the polygon.

The $\angle s$ AOB, BOC, etc., are equal, § 180

(*in the same $\odot$ equal arcs subtend equal $\angle s$ at the centre*).

$\therefore$ the $\angle AOB = 4$ rt. $\angle s$ divided by the number of $\angle s$ about O.

But the number of $\angle s$ about $O = n$, the number of sides of the polygon.

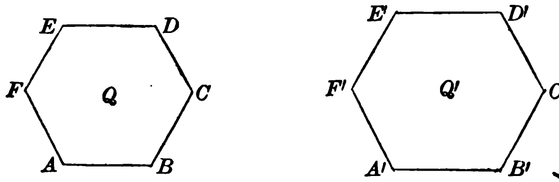
$$\therefore \angle AOB = \frac{4 \text{ rt. } \angle s}{n}.$$

Q. E. D.

371. Corollary. The radius drawn to any vertex of a regular polygon bisects the angle at that vertex.

PROPOSITION IV. THEOREM.

372. *Two regular polygons of the same number of sides are similar.*



Let Q and Q' be two regular polygons, each having n sides.

We are to prove Q *and* Q' *similar polygons.*

The sum of the interior $\angle s$ of each polygon is equal to 2 rt. $\angle s$ $(n-2)$, § 157

(*the sum of the interior $\angle s$ of a polygon is equal to 2 rt. $\angle s$ taken as many times less 2 as the polygon has sides*).

$$\text{Each } \angle \text{ of the polygon } Q = \frac{2 \text{ rt. } \angle s\ (n-2)}{n}, \qquad \S\ 158$$

(*for the $\angle s$ of a regular polygon are all equal, and hence each $\angle$ is equal to the sum of the $\angle s$ divided by their number*).

$$\text{Also, each } \angle \text{ of } Q' = \frac{2 \text{ rt. } \angle s\ (n-2)}{n}. \qquad \S\ 158$$

$\therefore$ the two polygons Q and Q' are mutually equiangular.

Moreover, $\frac{AB}{BC} = 1$, § 363

(*the sides of a regular polygon are all equal*);

and $\frac{A'B'}{B'C'} = 1$, § 363

$\therefore \frac{AB}{BC} = \frac{A'B'}{B'C'}$, Ax. 1

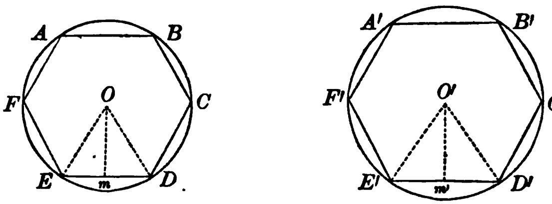
$\therefore$ the two polygons have their homologous sides proportional;

$\therefore$ the two polygons are similar. § 278

Q. E. D.

Proposition V. Theorem.

373. *The homologous sides of similar regular polygons have the same ratio as the radii of their circumscribed circles, and, also as the radii of their inscribed circles.*



Let O and O' be the centres of the two similar regular polygons $A\,B\,C$, etc., and $A'\,B'\,C'$, etc.

From O and O' draw $O\,E$, $O\,D$, $O'\,E'$, $O'\,D'$, also the ⊥s $O\,m$ and $O'\,m'$.

$O\,E$ and $O'\,E'$ are radii of the circumscribed ⊙s, § 367

and $O\,m$ and $O'\,m'$ are radii of the inscribed ⊙s. § 368

We are to prove $\dfrac{E\,D}{E'\,D'} = \dfrac{O\,E}{O'\,E'} = \dfrac{O\,m}{O'\,m'}$.

In the △s $O\,E\,D$ and $O'\,E'\,D'$

the ∠s $O\,E\,D$, $O\,D\,E$, $O'\,E'\,D'$ and $O'\,D'\,E'$ are equal, § 371

(being halves of the equal ∠s $F\,E\,D$, $E\,D\,C$, $F'\,E'\,D'$ and $E'\,D'\,C'$);

∴ the △s $O\,E\,D$ and $O'\,E'\,D'$ are similar, § 280

(if two △s have two ∠s of the one equal respectively to two ∠s of the other, they are similar).

$$\therefore \frac{E\,D}{E'\,D'} = \frac{O\,E}{O'\,E'}, \qquad \text{§ 278}$$

(the homologous sides of similar △s are proportional).

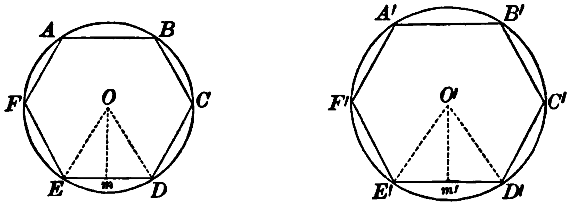
Also, $$\frac{E\,D}{E'\,D'} = \frac{O\,m}{O'\,m'}, \qquad \text{§ 297}$$

(the homologous altitudes of similar △s have the same ratio as their homologous bases).

Q. E. D.

PROPOSITION VI. THEOREM.

374. *The perimeters of similar regular polygons have the same ratio as the radii of their circumscribed circles, and, also as the radii of their inscribed circles.*



Let P and P' represent the perimeters of the two similar regular polygons ABC, etc., and $A'B'C'$, etc.

From centres O, O' draw OE, $O'E'$, and ⊥s Om and $O'm'$.

We are to prove $\dfrac{P}{P'} = \dfrac{OE}{O'E'} = \dfrac{Om}{O'm'}$.

$$\frac{P}{P'} = \frac{ED}{E'D'}, \qquad \S\ 295$$

(*the perimeters of similar polygons have the same ratio as any two homologous sides*).

Moreover, $$\frac{OE}{O'E'} = \frac{ED}{E'D'}, \qquad \S\ 373$$

(*the homologous sides of similar regular polygons have the same ratio as the radii of their circumscribed* ⓢ).

Also $$\frac{Om}{O'm'} = \frac{ED}{E'D'}, \qquad \S\ 373$$

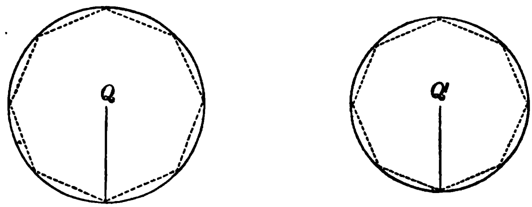
(*the homologous sides of similar regular polygons have the same ratio as the radii of their inscribed* ⓢ).

$$\therefore \frac{P}{P'} = \frac{OE}{O'E'} = \frac{Om}{O'm'}.$$

Q. E. D.

Proposition VII. Theorem.

375. *The circumferences of circles have the same ratio as their radii.*



Let C and C' be the circumferences, R and R' the radii of the two circles Q and Q'.

We are to prove $C : C' :: R : R'$.

Inscribe in the ⓢ two regular polygons of the same number of sides.

Conceive the number of the sides of these similar regular polygons to be indefinitely increased, the polygons continuing to be inscribed, and to have the same number of sides.

Then the perimeters will continue to have the same ratio as the radii of their circumscribed circles, § 374

(the perimeters of similar regular polygons have the same ratio as the radii of their circumscribed ⓢ),

and will approach indefinitely to the circumferences as their limits.

∴ the circumferences will have the same ratio as the radii of their circles, § 199

$$\therefore C : C' :: R : R'.$$

Q. E. D.

376. COROLLARY. By multiplying by 2, both terms of the ratio $R : R'$, we have

$$C : C' :: 2R : 2R';$$

that is, the circumferences of circles are to each other as their diameters.

Since $$C : C' :: 2R : 2R',$$

$$C : 2R :: C' : 2R', \qquad \S\ 262$$

or, $$\frac{C}{2R} = \frac{C'}{2R'}.$$

That is, the ratio of the circumference of a circle to its diameter is a constant quantity.

This constant quantity is denoted by the Greek letter π.

377. SCHOLIUM. The ratio π is incommensurable, and therefore can be expressed only approximately in figures. The letter π, however, is used to *represent* its *exact* value.

Ex. 1. Show that two triangles which have an angle of the one equal to the supplement of the angle of the other are to each other as the products of the sides including the supplementary angles.

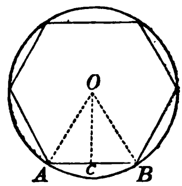
2. Show, geometrically, that the square described upon the sum of two straight lines is equivalent to the sum of the squares described upon the two lines *plus* twice their rectangle.

3. Show, geometrically, that the square described upon the difference of two straight lines is equivalent to the sum of the squares described upon the two lines *minus* twice their rectangle.

4. Show, geometrically, that the rectangle of the sum and difference of two straight lines is equivalent to the difference of the squares on those lines.

Proposition VIII. Theorem.

378. *If the number of sides of a regular inscribed polygon be increased indefinitely, the apothem will be an increasing variable whose limit is the radius of the circle.*



In the right triangle $O C A$, let $O A$ be denoted by R, $O C$ by r, and $A C$ by b.

We are to prove $\quad lim. (r) = R.$

$r < R,$ § 52

(a ⊥ is the shortest distance from a point to a straight line).

And $\quad R - r < b,$ § 97

(one side of a △ is greater than the difference of the other two sides).

By increasing the number of sides of the polygon indefinitely, $A B$, that is, $2 b$, can be made less than any assigned quantity.

$\therefore$ b, *the half* of $2 b$, can be made less than any assigned quantity.

$\therefore$ $R - r$, which is *less* than b, can be made less than any assigned quantity.

$\therefore lim. (R - r) = 0.$

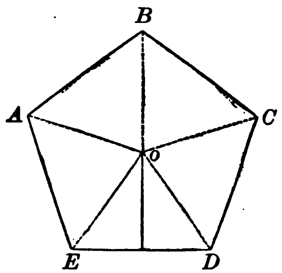
$\therefore R - lim. (r) = 0.$ § 199

$\therefore lim. (r) = R.$

Q. E. D.

PROPOSITION IX. THEOREM.

379. *The area of a regular polygon is equal to one-half the product of its apothem by its perimeter.*



Let P represent the perimeter and R the apothem of the regular polygon ABC, etc.

We are to prove the area of ABC, etc., $= \frac{1}{2} R \times P$.

Draw OA, OB, OC, etc.

The polygon is divided into as many $\triangle$ as it has sides.

The apothem is the common altitude of these $\triangle$,

and the area of each $\triangle$ is equal to $\frac{1}{2} R$ multiplied by the base. § 324

$\therefore$ the area of all the $\triangle$ is equal to $\frac{1}{2} R$ multiplied by the sum of all the bases.

But the sum of the areas of all the $\triangle$ is equal to the area of the polygon,

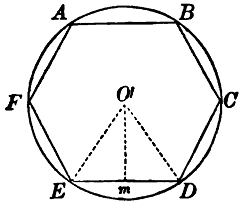
and the sum of all the bases of the $\triangle$ is equal to the perimeter of the polygon.

$\therefore$ the area of the polygon $= \frac{1}{2} R \times P$.

Q. E. D.

Proposition X. Theorem.

380. *The area of a circle is equal to one-half the product of its radius by its circumference.*



Let R represent the radius, and C the circumference of a circle.

We are to prove *the area of the circle* $= \frac{1}{2} R \times C$.

Inscribe any regular polygon, and denote its perimeter by P, and its apothem by r.

Then the area of this polygon $= \frac{1}{2} r \times P$, § 379

(*the area of a regular polygon is equal to one-half the product of its apothem by the perimeter*).

Conceive the number of sides of this polygon to be indefinitely increased, the polygon still continuing to be regular and inscribed.

Then the perimeter of the polygon approaches the circumference of the circle as its limit,

the apothem, the radius as its limit, § 378

and the area of the polygon approaches the $\odot$ as its limit.

But the area of the polygon continues to be equal to one-half the product of the apothem by the perimeter, however great the number of sides of the polygon.

$\therefore$ the area of the $\odot = \frac{1}{2} R \times C$. § 199

Q. E. D.

381. Corollary 1. Since $\frac{C}{2R} = \pi$, § 376

$$\therefore C = 2\pi R.$$

In the equality, the area of the $\odot = \frac{1}{2} R \times C$,
substitute $2\pi R$ for C;
then the area of the $\odot = \frac{1}{2} R \times 2\pi R$,
$= \pi R^2$.

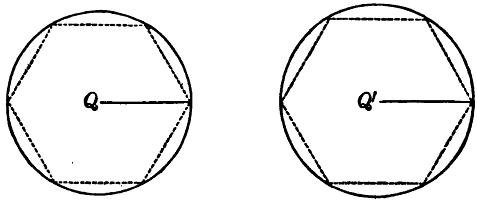
That is, *the area of a* $\odot = \pi$ *times the square on its radius.*

382. Cor. 2. *The area of a sector equals* $\frac{1}{2}$ *the product of its radius by its arc;* for the sector is such part of the circle as its arc is of the circumference.

383. Def. In different circles *similar arcs, similar sectors,* and *similar segments,* are such as correspond to equal angles at the centre.

Proposition XI. Theorem.

384. *Two circles are to each other as the squares on their radii.*



Let R and R' be the radii of the two circles Q and Q'.

We are to prove $\frac{Q}{Q'} = \frac{R^2}{R'^2}$.

Now $Q = \pi R^2$, § 381
(*the area of a* $\odot = \pi$ *times the square on its radius*),

and $Q' = \pi R'^2$. § 381

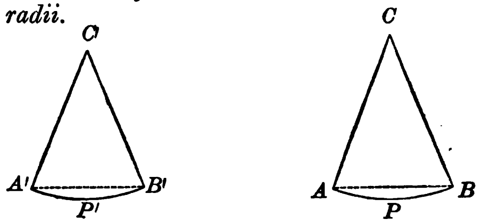
Then $\frac{Q}{Q'} = \frac{\pi R^2}{\pi R'^2} = \frac{R^2}{R'^2}$.

Q. E. D.

385. Corollary. *Similar arcs,* being like parts of their respective circumferences, *are to each other as their radii; similar sectors,* being like parts of their respective circles, *are to each other as the squares on their radii.*

PROPOSITION XII. THEOREM.

386. *Similar segments are to each other as the squares on their radii.*



Let AC and $A'C'$ be the radii of the two similar segments ABP and $A'B'P'$.

We are to prove $\dfrac{ABP}{A'B'P'} = \dfrac{\overline{AC}^2}{\overline{A'C'}^2}$.

The sectors ACB and $A'C'B'$ are similar, § 383
(*having the* ∠s *at the centre,* C *and* C', *equal*).

In the △s ACB and $A'C'B'$

$$\angle C = \angle C', \quad \text{§ 383}$$
(*being corresponding* ∠s *of similar sectors*).

$$AC = CB, \quad \text{§ 163}$$
$$A'C' = C'B'; \quad \text{§ 163}$$

∴ the △s ACB and $A'C'B'$ are similar, § 284
(*having an* ∠ *of the one equal to an* ∠ *of the other, and the including sides proportional*).

Now $\dfrac{\text{sector } ACB}{\text{sector } A'C'B'} = \dfrac{\overline{AC}^2}{\overline{A'C'}^2}$, § 385
(*similar sectors are to each other as the squares on their radii*);

and $\dfrac{\triangle ACB}{\triangle A'C'B'} = \dfrac{\overline{AC}^2}{\overline{A'C'}^2}$, § 342
(*similar* △s *are to each other as the squares on their homologous sides*).

Hence $\dfrac{\text{sector } ACB - \triangle ACB}{\text{sector } A'C'B' - \triangle A'C'B'} = \dfrac{\overline{AC}^2}{\overline{A'C'}^2}$,

or, $\dfrac{\text{segment } ABP}{\text{segment } A'B'P'} = \dfrac{\overline{AC}^2}{\overline{A'C'}^2}$, § 271
(*if two quantities be increased or diminished by like parts of each, the results will be in the same ratio as the quantities themselves*).

Q. E. D.

Exercises.

1. Show that an equilateral polygon circumscribed about a circle is regular if the number of its sides be *odd*.

2. Show that an equiangular polygon inscribed in a circle is regular if the number of its sides be *odd.*

3. Show that *any* equiangular polygon circumscribed about a circle is regular.

4. Show that the side of a circumscribed equilateral triangle is double the side of an inscribed equilateral triangle.

5. Show that the area of a regular inscribed hexagon is three-fourths of that of the regular circumscribed hexagon.

6. Show that the area of a regular inscribed hexagon is a mean proportional between the areas of the inscribed and circumscribed equilateral triangles.

7. Show that the area of a regular inscribed octagon is equal to that of a rectangle whose adjacent sides are equal to the sides of the inscribed and circumscribed squares.

8. Show that the area of a regular inscribed dodecagon is equal to three times the square on the radius.

9. Given the diameter of a circle 50; find the area of the circle. Also, find the area of a sector of 80° of this circle.

10. Three equal circles touch each other externally and thus inclose one acre of ground; find the radius in rods of each of these circles.

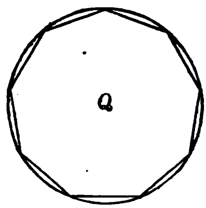
11. Show that in two circles of different radii, angles at the centres subtended by arcs of equal length are to each other inversely as the radii.

12. Show that the square on the side of a regular inscribed pentagon, minus the square on the side of a regular inscribed decagon, is equal to the square on the radius.

On Constructions.

Proposition XIII. Problem.

387. *To inscribe a regular polygon of any number of sides in a given circle.*



Let Q be the given circle, and n the number of sides of the polygon.

It is required to inscribe in Q, a regular polygon having n sides.

Divide the circumference of the ⊙ into n equal arcs.

Join the extremities of these arcs.

Then we have the polygon required.

For the polygon is equilateral, § 181

(in the same ⊙ equal arcs are subtended by equal chords);

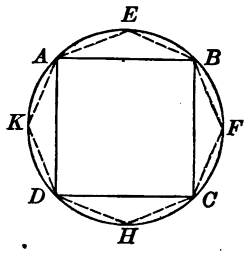
and the polygon is also regular, § 364

(an equilateral polygon inscribed in a ⊙ is regular).

Q. E. F.

Proposition XIV. Problem.

388. *To inscribe in a given circle a regular polygon which has double the number of sides of a given inscribed regular polygon.*



Let $ABCD$ be the given inscribed polygon.

It is required to inscribe a regular polygon having double the number of sides of $ABCD$.

Bisect the arcs AB, BC, etc.

Draw AE, EB, BF, etc.,

The polygon $AEBFC$, etc., is the polygon required.

For the chords AB, BC, etc., are equal, § 363
(being sides of a regular polygon).

$\therefore$ the arcs AB, BC, etc., are equal, § 182
(in the same ⊙ equal chords subtend equal arcs).

Hence the halves of these arcs are equal,

or, AE, EB, BF, FC, etc., are equal;

$\therefore$ the polygon $AEBF$, etc., is equilateral.

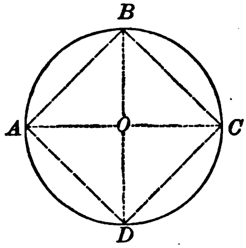
The polygon is also regular, § 364
(an equilateral polygon inscribed in a ⊙ is regular);

and has double the number of sides of the given regular polygon.

Q. E. F.

PROPOSITION XV. PROBLEM.

389. *To inscribe a square in a given circle.*



Let O be the centre of the given circle.

It is required to inscribe a square in the circle.

Draw the two diameters AC and $BD \perp$ to each other.

Join AB, BC, CD, and DA.

Then $ABCD$ is the square required.

For, the $\angle$s ABC, BCD, etc., are rt. $\angle$s, § 204
(being inscribed in a semicircle),

and the sides AB, BC, etc., are equal, § 181
(in the same ⊙ equal arcs are subtended by equal chords);

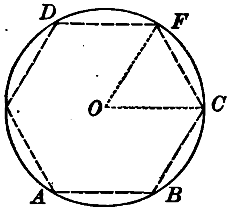
$\therefore$ the figure $ABCD$ is a square, § 127
(having its sides equal and its $\angle$s rt. $\angle$s).

Q. E. F.

390. COROLLARY. By bisecting the arcs AB, BC, etc., a regular polygon of 8 sides may be inscribed; and, by continuing the process, regular polygons of 16, 32, 64, etc., sides may be inscribed.

PROPOSITION XVI. PROBLEM.

391. *To inscribe in a given circle a regular hexagon.*



Let O be the centre of the given circle.

It is required to inscribe in the given ⊙ a regular hexagon.

From O draw any radius, as OC.

From C as a centre, with a radius equal to OC, describe an arc intersecting the circumference at F.

Draw OF and CF.

Then CF is a side of the regular hexagon required.

For the $\triangle\ OFC$ is equilateral, Cons.

and equiangular, § 112

$\therefore$ the $\angle\ FOC$ is $\frac{1}{3}$ of 2 rt. $\angle$s, or, $\frac{1}{6}$ of 4 rt. $\angle$s. § 98

$\therefore$ the arc FC is $\frac{1}{6}$ of the circumference $ABCF$,

$\therefore$ the chord FC, which subtends the arc FC, is a side of a regular hexagon;

and the figure CFD, etc., formed by applying the radius six times as a chord, is the hexagon required.

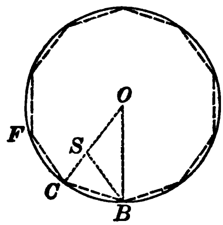
Q. E. F.

392. COROLLARY 1. By joining the alternate vertices A, C, D, an equilateral $\triangle$ is inscribed in a circle.

393. COR. 2. By bisecting the arcs AB, BC, etc., a regular polygon of 12 sides may be inscribed in a circle; and, by continuing the process, regular polygons of 24, 48, etc., sides may be inscribed.

PROPOSITION XVII. PROBLEM.

394. *To inscribe in a given circle a regular decagon.*



Let O be the centre of the given circle.

It is required to inscribe in the given ⊙ *a regular decagon.*

Draw the radius OC,

and divide it in extreme and mean ratio, so that OC shall be to OS as OS is to SC. § 311

From C as a centre, with a radius equal to OS,

describe an arc intersecting the circumference at B.

Draw BC, BS, and BO.

Then BC is a side of the regular decagon required.

For $OC : OS :: OS : SC$, Cons.

and $BC = OS$. Cons.

Substitute for OS its equal BC,

then $OC : BC :: BC : SC$.

Moreover the $\angle OCB = \angle SCB$, Iden.

∴ the $\triangle$s OCB and BCS are similar, § 284

(*having an* ∠ *of the one equal to an* ∠ *of the other, and the including sides proportional*).

But the $\triangle OCB$ is isosceles, § 160

(*its sides O C and O B being radii of the same circle*).

∴ the $\triangle BCS$, which is similar to the $\triangle OCB$, is isosceles,

and $BS = BC$. § 114

But $OS = BC$, Cons.

$\therefore OS = BS$, Ax. 1

$\therefore$ the $\triangle SOB$ is isosceles,

and the $\angle O = \angle SBO$, § 112

(being opposite equal sides).

But the $\angle CSB = \angle O + \angle SBO$, § 105

(the exterior $\angle$ of a $\triangle$ is equal to the sum of the two opposite interior $\angle$s).

$\therefore$ the $\angle CSB = 2 \angle O$.

$\angle SCB (= \angle CSB) = 2 \angle O$, § 112

and $\angle OBC (= \angle SCB) = 2 \angle O$. § 112

$\therefore$ the sum of the $\angle$s of the $\triangle OCB = 5 \angle O$.

$\therefore 5 \angle O = 2$ rt. $\angle$s, § 98

and $\angle O = \frac{1}{5}$ of 2 rt. $\angle$s, or $\frac{1}{10}$ of 4 rt. $\angle$s.

$\therefore$ the arc BC is $\frac{1}{10}$ of the circumference, and

$\therefore$ the chord BC is a side of a regular inscribed decagon.

Hence, to inscribe a regular decagon, divide the radius in extreme and mean ratio, and apply the greater segment ten times as a chord.

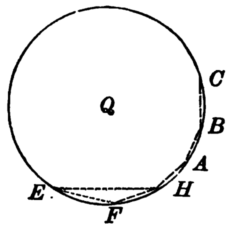
Q. E. F.

395. Corollary 1. By joining the alternate vertices of a regular inscribed decagon, a regular pentagon may be inscribed.

396. Cor. 2. By bisecting the arcs BC, CF, etc., a regular polygon of 20 sides may be inscribed, and, by continuing the process, regular polygons of 40, 80, etc., sides may be inscribed.

PROPOSITION XVIII. PROBLEM.

397. *To inscribe in a given circle a regular pentedecagon, or polygon of fifteen sides.*



Let Q be the given circle.

It is required to inscribe in Q a regular pentedecagon.

Draw EH equal to a side of a regular inscribed hexagon, § 391

and EF equal to a side of a regular inscribed decagon. § 394

Join FH.

Then FH will be a side of a regular inscribed pentedecagon.

For the arc EH is $\frac{1}{6}$ of the circumference,

and the arc EF is $\frac{1}{10}$ of the circumference;

$\therefore$ the arc FH is $\frac{1}{6} - \frac{1}{10}$, or $\frac{1}{15}$, of the circumference.

$\therefore$ the chord FH is a side of a regular inscribed pentedecagon,

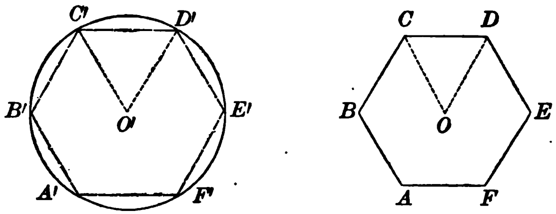
and by applying FH fifteen times as a chord, we have the polygon required.

Q. E. F.

398. COROLLARY. By bisecting the arcs FH, HA, etc., a regular polygon of 30 sides may be inscribed; and by continuing the process, regular polygons of 60, 120, etc. sides may be inscribed.

PROPOSITION XIX. PROBLEM.

399. *To inscribe in a given circle a regular polygon similar to a given regular polygon.*



Let $A\,B\,C\,D$, etc., be the given regular polygon, and $C'\,D'\,E'$ the given circle.

It is required to inscribe in $C'\,D'\,E'$ a regular polygon similar to $A\,B\,C\,D$, etc.

From O, the centre of the polygon $A\,B\,C\,D$, etc.

draw $O\,D$ and $O\,C$.

From O' the centre of the $\odot\ C'\,D'\,E'$,

draw $O'\,C'$ and $O'\,D'$,

making the $\angle\ O' = \angle\ O$.

Draw $C'\,D'$.

Then $C'\,D'$ will be a side of the regular polygon required.

For each polygon will have as many sides as the $\angle\ O$ $(= \angle\ O')$ is contained times in 4 rt. $\angle$s.

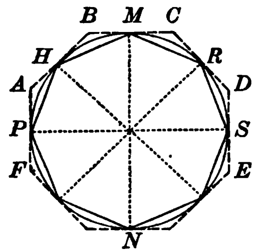
$\therefore$ the polygon $C'\,D'\,E'$, etc. is similar to the polygon $C\,D\,E$, etc., § 372

(*two regular polygons of the same number of sides are similar*).

Q. E. F.

PROPOSITION XX. PROBLEM.

400. *To circumscribe about a circle a regular polygon similar to a given inscribed regular polygon.*



Let $HMRS$, etc., be a given inscribed regular polygon.

It is required to circumscribe a regular polygon similar to $HMRS$, etc.

At the vertices H, M, R, etc., draw tangents to the ⊙, intersecting each other at A, B, C, etc.

Then the polygon $ABCD$, etc. will be the regular polygon required.

Since the polygon $ABCD$, etc.

has the same number of sides as the polygon $HMRS$, etc.,

it is only necessary to prove that $ABCD$, etc. is a regular polygon. § 372

In the $\triangle$ BHM and CMR,

$$HM = MR, \qquad \S\ 363$$

(being sides of a regular polygon),

the $\angle$s BHM, BMH, CMR, and CRM are equal, § 209
(being measured by halves of equal arcs);

$\therefore$ the $\triangle$s BHM and CMR are equal, § 107
(having a side and two adjacent $\angle$s of the one equal respectively to a side and two adjacent $\angle$s of the other).

$\therefore \angle B = \angle C,$
(being homologous $\angle$s of equal $\triangle$s).

In like manner we may prove $\angle C = \angle D$, etc.

$\therefore$ the polygon $ABCD$, etc., is equiangular.

Since the $\triangle$s BHM, CMR, etc. are isosceles, § 241
(two tangents drawn from the same point to a $\odot$ are equal),

the sides BH, BM, CM, CR, etc. are equal,
(being homologous sides of equal isosceles $\triangle$s).

$\therefore$ the sides AB, BC, CD, etc. are equal, Ax. 6

and the polygon $ABCD$, etc. is equilateral.

Therefore the circumscribed polygon is regular and similar to the given inscribed polygon. § 372

Q. E. F.

Ex. Let R denote the radius of a regular inscribed polygon, r the apothem, a one side, A one angle, and C the angle at the centre; show that

1. In a regular inscribed triangle $a = R\sqrt{3}$, $r = \frac{1}{2}R$, $A = 60°$, $C = 120°$.

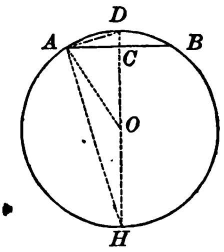
2. In an inscribed square $a = R\sqrt{2}$, $r = \frac{1}{2}R\sqrt{2}$, $A = 90°$, $C = 90°$.

3. In a regular inscribed hexagon $a = R$, $r = \frac{1}{2}R\sqrt{3}$, $A = 120°$, $C = 60°$.

4. In a regular inscribed decagon $a = \dfrac{R(\sqrt{5}-1)}{2}$, $r = \frac{1}{4}R\sqrt{10 + 2\sqrt{5}}$, $A = 144°$, $C = 36°$.

Proposition XXI. Problem.

401. *To find the value of the chord of one-half an arc, in terms of the chord of the whole arc and the radius of the circle.*



Let AB be the chord of arc AB and AD the chord of one-half the arc AB.

It is required to find the value of AD in terms of AB and R (radius).

From D draw DH through the centre O,

and draw OA.

HD is $\perp$ to the chord AB at its middle point C, § 60

(*two points, O and D, equally distant from the extremities, A and B, determine the position of a $\perp$ to the middle point of AB*).

The $\angle HAD$ is a rt. $\angle$, § 204

(*being inscribed in a semicircle*),

$\therefore \overline{AD}^2 = DH \times DC,$ § 289

(*the square on one side of a rt. $\triangle$ is equal to the product of the hypotenuse by the adjacent segment made by the $\perp$ let fall from the vertex of the rt. $\angle$*).

Now $DH = 2R,$

and $DC = DO - CO = R - CO;$

$\therefore \overline{AD}^2 = 2R(R - CO).$

Since $\quad ACO$ is a rt. $\triangle$,

$$\overline{AO}^2 = \overline{AC}^2 + \overline{CO}^2; \qquad \S\ 331$$

$$\therefore \overline{CO}^2 = \overline{AO}^2 - \overline{AC}^2.$$

$$\therefore CO = \sqrt{(\overline{AO}^2 - \overline{AC}^2)},$$

$$= \sqrt{R^2 - (\tfrac{1}{2} AB)^2},$$

$$= \sqrt{R^2 - \tfrac{1}{4} \overline{AB}^2},$$

$$= \sqrt{\frac{4R^2 - \overline{AB}^2}{4}},$$

$$= \frac{\sqrt{4R^2 - \overline{AB}^2}}{2}.$$

In the equation $\overline{AD}^2 = 2R(R - CO)$,

substitute for CO its value $\dfrac{\sqrt{4R^2 - \overline{AB}^2}}{2}$;

then $\quad \overline{AD}^2 = 2R\left(R - \dfrac{\sqrt{4R^2 - \overline{AB}^2}}{2}\right)$,

$$= 2R^2 - R\left(\sqrt{4R^2 - \overline{AB}^2}\right).$$

$$\therefore AD = \sqrt{2R^2 - R\left(\sqrt{4R^2 - \overline{AB}^2}\right)}.$$

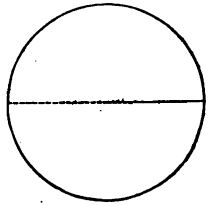
Q. E. F.

402. Corollary. If we take the radius equal to unity, the equation $AD = \sqrt{2R^2 - R\left(\sqrt{4R^2 - \overline{AB}^2}\right)}$ becomes

$$AD = \sqrt{2 - \sqrt{4 - \overline{AB}^2}}.$$

Proposition XXII. Problem.

403. *To compute the ratio of the circumference of a circle to its diameter, approximately.*



Let C be the circumference and R the radius of a circle.

Since $$\pi = \frac{C}{2R}, \qquad \text{§ 376}$$

$$\text{when } R = 1,\ \pi = \frac{C}{2}.$$

It is required to find the numerical value of π.

We make the following computations by the use of the formula obtained in the last proposition,

$$AD = \sqrt{2 - \sqrt{4 - \overline{AB}^2}},$$

when AB is a side of a regular hexagon:

In a polygon of

No. Sides.	Form of Computation.	Length of Side.	Perimeter.
12	$AD = \sqrt{2 - \sqrt{4 - 1^2}}$	.51763809	6.21165708
24	$AD = \sqrt{2 - \sqrt{4 - (.51763809)^2}}$	.26105238	6.26525722
48	$AD = \sqrt{2 - \sqrt{4 - (.26105238)^2}}$	.13080626	6.27870041
96	$AD = \sqrt{2 - \sqrt{4 - (.13080626)^2}}$	.06543817	6.28206396
192	$AD = \sqrt{2 - \sqrt{4 - (.06543817)^2}}$	.03272346	6.28290510
384	$AD = \sqrt{2 - \sqrt{4 - (.03272346)^2}}$	.01636228	6.28311544
768	$AD = \sqrt{2 - \sqrt{4 - (.01636228)^2}}$	.00818121	6.28316941

Hence we may consider 6.28317 as approximately the circumference of a ⊙ whose radius is unity.

$$\therefore \pi, \text{ which equals } \frac{C}{2}, = \frac{6.28317}{2}.$$

$$\therefore \pi = 3.14159 \text{ nearly.}$$

Q. E. F

On Isoperimetrical Polygons. — Supplementary.

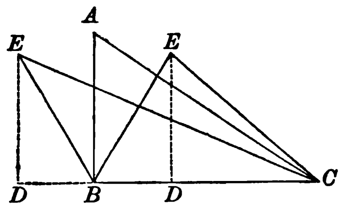
404. Def. *Isoperimetrical* figures are figures which have equal perimeters.

405. Def. Among magnitudes of the same kind, that which is greatest is a *Maximum*, and that which is smallest is a *Minimum*.

Thus the diameter of a circle is the maximum among all inscribed straight lines; and a perpendicular is the minimum among all straight lines drawn from a point to a given straight line.

Proposition XXIII. Theorem.

406. *Of all triangles having two sides respectively equal, that in which these sides include a right angle is the maximum.*



Let the triangles ABC and EBC have the sides AB and BC equal respectively to EB and BC; and let the angle ABC be a right angle.

We are to prove $\triangle ABC > \triangle EBC$.

From E, let fall the $\perp ED$.

The $\triangle$s ABC and EBC, having the same base BC, are to each other as their altitudes AB and ED, § 326

(*$\triangle$s having the same base are to each other as their altitudes*).

Now ED is $< EB$, § 52

(*a $\perp$ is the shortest distance from a point to a straight line*).

But $EB = AB$, Hyp.

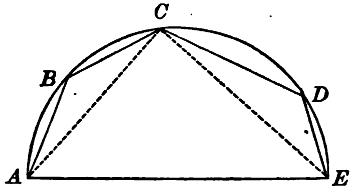
$\therefore ED$ is $< AB$.

$\therefore \triangle ABC > \triangle EBC$.

Q. E. D.

PROPOSITION XXIV. THEOREM.

407. *Of all polygons formed of sides all given but one, the polygon inscribed in a semicircle, having the undetermined side for its diameter, is the maximum.*



Let AB, BC, CD, and DE be the sides of a polygon inscribed in a semicircle having AE for its diameter.

We are to prove the polygon $ABCDE$ the maximum of polygons having the sides AB, BC, CD, and DE.

From *any* vertex, as C, draw CA and CE.

Then the $\angle ACE$ is a rt. $\angle$, § 204

(being inscribed in a semicircle).

Now the polygon is divided into three parts, ABC, CDE, and ACE.

The parts ABC and CDE will remain the same, if the $\angle ACE$ be increased or diminished;

but the part ACE will be diminished, § 406

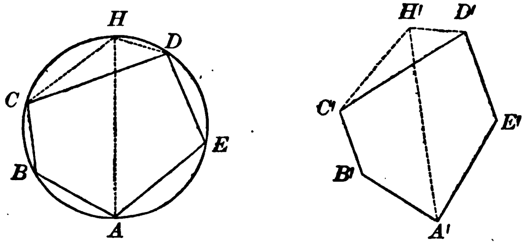
(of all △ having two sides respectively equal, that in which these sides include a rt. $\angle$ is the maximum).

$\therefore ABCDE$ is the maximum polygon.

Q. E. D.

PROPOSITION XXV. THEOREM.

408. *The maximum of all polygons formed of given sides can be inscribed in a circle.*



Let $ABCDE$ be a polygon inscribed in a circle, and $A'B'C'D'E'$ be a polygon, equilateral with respect to $ABCDE$, but which cannot be inscribed in a circle.

We are to prove

the polygon $ABCDE >$ the polygon $A'B'C'D'E'$.

Draw the diameter AH.

Join CH and DH.

Upon $C'D'$ ($= CD$) construct the $\triangle C'H'D' = \triangle CHD$,

and draw $A'H'$.

Now the polygon $ABCH >$ the polygon $A'B'C'H'$, § 407

(of all polygons formed of sides all given but one, the polygon inscribed in a semicircle having the undetermined side for its diameter, is the maximum).

And the polygon $AEDH >$ the polygon $A'E'D'H'$. § 407

Add these two inequalities, then

the polygon $ABCHDE >$ the polygon $A'B'C'H'D'E'$.

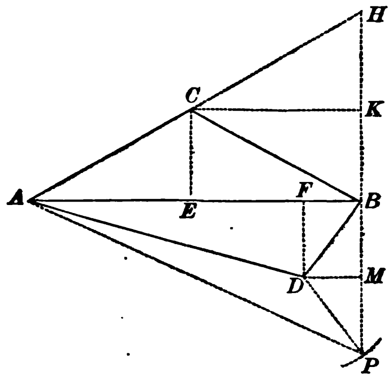
Take away from the two figures the equal $\triangle$s CHD and $C'H'D'$.

Then the polygon $ABCDE >$ the polygon $A'B'C'D'E'$.

Q. E. D.

PROPOSITION XXVI. THEOREM.

409. *Of all triangles having the same base and equal perimeters, the isosceles triangle is the maximum.*



Let the $\triangle$s ACB and ADB have equal perimeters, and let the $\triangle\ ACB$ be isosceles.

We are to prove $\triangle\ ACB > \triangle\ ADB$.

Draw the $\perp$s CE and DF.

$$\frac{\triangle\ ACB}{\triangle\ ABD} = \frac{CE}{DF}, \qquad \S\ 326$$

(*$\triangle$s having the same base are to each other as their altitudes*).

Produce AC to H, making $CH = AC$.

Draw HB.

The $\angle\ ABH$ is a rt. $\angle$, for it will be inscribed in the semicircle drawn from C as a centre, with the radius CB.

From C let fall the $\perp$ CK;

and from D as a centre, with a radius equal to DB,

describe an arc cutting HB produced, at P.

Draw DP and AP,

and let fall the $\perp$ DM.

Since $AH = AC + CB = AD + DB$,

and $AP < AD + DP$;

$\therefore AP < AD + DB$;

$\therefore AH > AP$.

$\therefore BH > BP$. § 56

Now $BK = \frac{1}{2} BH$, § 113

(a $\perp$ drawn from the vertex of an isosceles $\triangle$ bisects the base),

and $BM = \frac{1}{2} BP$. § 113

But $CE = BK$, § 135

($\parallel$s comprehended between $\parallel$s are equal);

and $DF = BM$, § 135

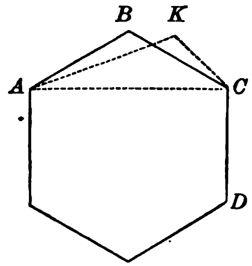
$\therefore CE > DF$.

$\therefore \triangle ACB > \triangle ADB$.

Q. E. D.

PROPOSITION XXVII. THEOREM.

410. *The maximum of isoperimetrical polygons of the same number of sides is equilateral.*



Let $A B C D$, etc., be the maximum of isoperimetrical polygons of any given number of sides.

We are to prove $A B$, $B C$, $C D$, *etc., equal.*

Draw $A C$.

The $\triangle$ $A B C$ must be the maximum of all the $\triangle$s which are formed upon $A C$ with a perimeter equal to that of $\triangle$ $A B C$.

Otherwise, a greater $\triangle A K C$ could be substituted for $\triangle A B C$, without changing the perimeter of the polygon.

But this is inconsistent with the hypothesis that the polygon $A B C D$, etc., is the maximum polygon.

$\therefore$ the $\triangle$ $A B C$, is isosceles, § 409

(*of all $\triangle$s having the same base and equal perimeters, the isosceles $\triangle$ is the maximum*).

In like manner it may be proved that $B C = C D$, etc.

Q. E. D.

411. COROLLARY. The maximum of isoperimetrical polygons of the same number of sides is a regular polygon.

For, it is equilateral, § 410

(*the maximum of isoperimetrical polygons of the same number of sides is equilateral*).

Also it can be inscribed in a $\odot$, § 408

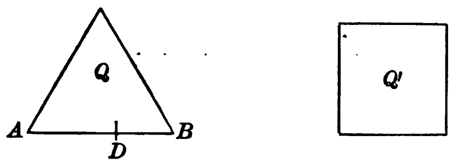
(*the maximum of all polygons formed of given sides can be inscribed in a $\odot$*).

Hence it is regular, § 364

(*an equilateral polygon inscribed in a $\odot$ is regular*).

PROPOSITION XXVIII. THEOREM.

412. *Of isoperimetrical regular polygons, that is greatest which has the greatest number of sides.*



Let Q be a regular polygon of three sides, and Q' be a regular polygon of four sides, each having the same perimeter.

We are to prove $Q' > Q$.

In any side $A\,B$ of Q, take any point D.

The polygon Q may be considered an irregular polygon of four sides, in which the sides $A\,D$ and $D\,B$ make with each other an $\angle$ equal to two rt. $\angle$s.

Then the irregular polygon Q, of four sides is less than the regular isoperimetrical polygon Q' of four sides, § 411

(the maximum of isoperimetrical polygons of the same number of sides is a regular polygon).

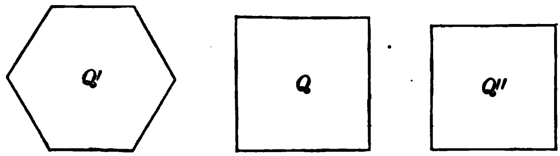
In like manner it may be shown that Q' is less than a regular isoperimetrical polygon of five sides, and so on.

Q. E. D.

413. COROLLARY. Of all isoperimetrical plane figures the circle is the maximum.

Proposition XXIX. Theorem.

414. *If a regular polygon be constructed with a given area, its perimeter will be the less the greater the number of its sides.*



Let Q and Q' be regular polygons having the same area, and let Q' have the greater number of sides.

We are to prove the perimeter of $Q >$ the perimeter of Q'.

Let Q'' be a regular polygon having the same perimeter as Q', and the same number of sides as Q.

Then Q' is $> Q''$, § 412
(*of isoperimetrical regular polygons, that is the greatest which has the greatest number of sides*).

But $Q = Q'$,

$\therefore Q$ is $> Q''$.

$\therefore$ the perimeter of Q is $>$ the perimeter of Q''.

But the perimeter of $Q' =$ the perimeter of Q'', Cons.

$\therefore$ the perimeter of Q is $>$ that of Q'.

Q. E. D.

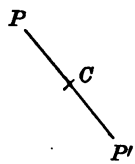
415. Corollary. The circumference of a circle is less than the perimeter of any other plane figure of equal area.

On Symmetry. — Supplementary.

416. Two points are *Symmetrical* when they are situated on opposite sides of, and *at equal distances from*, a fixed point, line, or plane, taken as an object of reference.

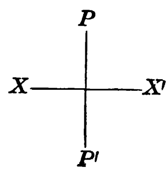
417. When a point is taken as an object of reference, it is called the *Centre of Symmetry;* when a line is taken, it is called the *Axis of Symmetry;* when a plane is taken, it is called the *Plane of Symmetry.*

418. *Two points* are symmetrical with respect to a *centre*, if the centre bisect the straight line terminated by these points. Thus, P, P' are symmetrical with respect to C, if C bisect the straight line PP'.

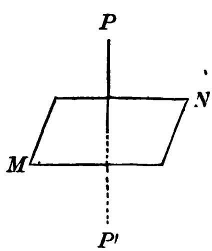


419. The distance of either of the two symmetrical points from the centre of symmetry is called the *Radius of Symmetry*. Thus either CP or CP' is the radius of symmetry.

420. *Two points* are symmetrical with respect to an *axis*, if the axis bisect at right angles the straight line terminated by these points. Thus, P, P' are symmetrical with respect to the axis XX', if XX' bisect PP' at right angles.



421. *Two points* are symmetrical with respect to a *plane*, if the plane bisect at right angles the straight line terminated by these points. Thus P, P' are symmetrical with respect to MN, if MN bisect PP' at right angles.



422. *Two plane figures* are symmetrical with respect to a *centre*, an *axis*, or a *plane*, if every point of either figure have its corresponding symmetrical point in the other.

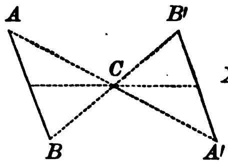


Fig. 1.

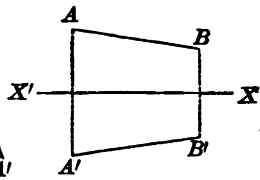


Fig. 2.

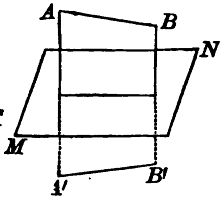


Fig. 3.

Thus, the lines $A\,B$ and $A'\,B'$ are symmetrical with respect to the centre C (Fig. 1), to the axis $X\,X'$ (Fig. 2), to the plane $M\,N$ (Fig. 3), if every point of either have its corresponding symmetrical point in the other.

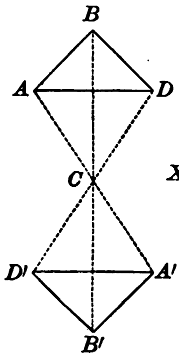


Fig. 4.

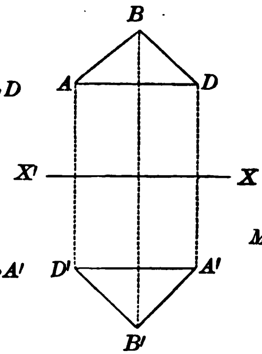


Fig. 5.

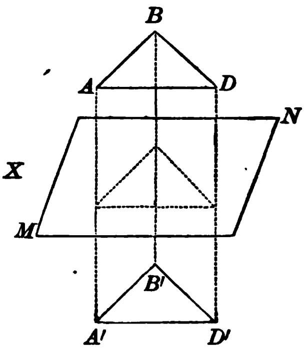


Fig. 6.

Also, the triangles $A\,B\,D$ and $A'\,B'\,D'$ are symmetrical with respect to the centre C (Fig. 4), to the axis $X\,X'$ (Fig. 5), to the plane $M\,N$ (Fig. 6), if every point in the perimeter of either have its corresponding symmetrical point in the perimeter of the other.

423. Def. In two symmetrical figures the corresponding symmetrical points and lines are called *homologous*.

Two symmetrical figures with respect to a centre can be brought into coincidence by revolving one of them in its own plane about the centre, every radius of symmetry revolving through two right angles at the same time.

Two symmetrical figures with respect to an axis can be brought into coincidence by the revolution of either about the axis until it comes into the plane of the other.

424. Def. A single figure is a *symmetrical figure*, either when it can be divided by an axis, or plane, into two figures symmetrical with respect to that axis or plane; or, when it has a centre such that every straight line drawn through it cuts the perimeter of the figure in two points which are symmetrical with respect to that centre.

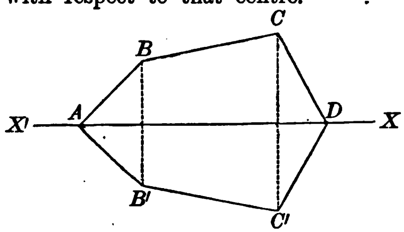


Fig. 1.

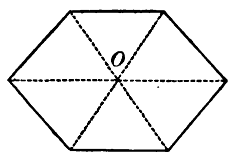


Fig. 2.

Thus, Fig. 1 is a symmetrical figure with respect to the axis XX', if divided by XX' into figures $ABCD$ and $AB'C'D$ which are symmetrical with respect to XX'.

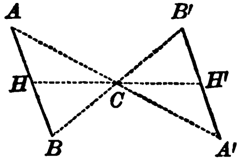
And, Fig. 2 is a symmetrical figure with respect to the centre O, if the centre O bisect every straight line drawn through it and terminated by the perimeter.

Every such straight line is called a *diameter*.

The circle is an illustration of a single figure symmetrical with respect to its centre as the *centre of symmetry*, or to any diameter as the *axis of symmetry*.

PROPOSITION XXX. THEOREM.

425. *Two equal and parallel lines are symmetrical with respect to a centre.*



Let $A B$ and $A' B'$ be equal and parallel lines.

We are to prove $A B$ *and* $A' B'$ *symmetrical.*

Draw $A A'$ and $B B'$, and through the point of their intersection C, draw any other line $H C H'$, terminated in $A B$ and $A' B'$.

In the $\triangle$s $C A B$ and $C A' B'$

$A B = A' B'$, Hyp.

also, $\angle$s A and $B = \angle$s A' and B' respectively, § 68
(*being alt.-int.* $\angle$s),

$\therefore \triangle C A B = \triangle C A' B'$; § 107

$\therefore C A$ and $C B = C A'$ and $C B'$ respectively,
(*being homologous sides of equal* $\triangle$s).

Now in the $\triangle$s $A C H$ and $A' C H'$

$A C = A' C$,

$\angle$s A and $A C H = \angle$s A' and $A' C H'$ respectively,

$\therefore \triangle A C H = \triangle A' C H'$, § 107
(*having a side and two adj.* $\angle$s *of the one equal respectively to a side and two adj.* $\angle$s *of the other*).

$\therefore C H = C H'$,
(*being homologous sides of equal* $\triangle$s).

$\therefore H'$ is the symmetrical point of H.

But H is *any* point in $A B$;

$\therefore$ *every* point in $A B$ has its symmetrical point in $A' B'$.

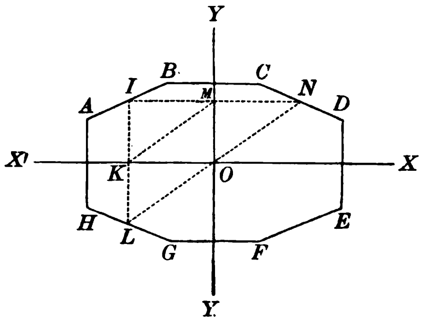
$\therefore A B$ and $A' B'$ are symmetrical with respect to C as a centre of symmetry.

Q. E. D.

426. COROLLARY. If the extremities of one line be respectively the symmetricals of another line with respect to the ·ame centre, the two lines are symmetrical with respect to that ·tre.

Proposition XXXI. Theorem.

427. *If a figure be symmetrical with respect to two axes perpendicular to each other, it is symmetrical with respect to their intersection as a centre.*



Let the figure $ABCDEFGH$ be symmetrical to the two axes XX', YY' which intersect at O.

We are to prove O the centre of symmetry of the figure.

Let I be any point in the perimeter of the figure.

Draw $IKL \perp$ to XX', and $IMN \perp$ to YY'.

Join LO, ON, and KM.

Now $KI = KL$, § 420

(the figure being symmetrical with respect to XX').

But $KI = OM$, § 135

(∥s comprehended between ∥s are equal).

$\therefore KL = OM$. Ax. 1

$\therefore KLOM$ is a ▱, § 136

(having two sides equal and parallel).

$\therefore LO$ is equal and parallel to KM, § 134

(being opposite sides of a ▱).

In like manner we may prove ON equal and parallel to KM.

Hence the points L, O, and N are in the same straight line drawn through the point O ∥ to KM.

Also $LO = ON$,

(since each is equal to KM).

$\therefore$ any straight line LON, drawn through O, is bisected at O.

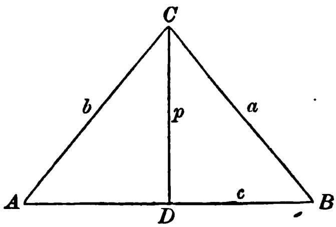
$\therefore O$ is the centre of symmetry of the figure. § 424

Q. E. D.

Exercises.

1. The area of any triangle may be found as follows: From half the sum of the three sides subtract each side severally, multiply together the half sum and the three remainders, and extract the square root of the product.

Denote the sides of the triangle $A B C$ by a, b, c, the altitude by p, and $\frac{a+b+c}{2}$ by s.



Show that

$$a^2 = b^2 + c^2 - 2c \times AD,$$

$$AD = \frac{b^2 + c^2 - a^2}{2c};$$

and show that

$$p^2 = b^2 - \frac{(b^2 + c^2 - a^2)^2}{4c^2},$$

$$p = \frac{\sqrt{4b^2c^2 - (b^2 + c^2 - a^2)^2}}{2c},$$

$$p = \frac{\sqrt{(b+c+a)(b+c-a)(a+b-c)(a-b+c)}}{2c}.$$

Hence, show that area of $\triangle ABC$, which is equal to $\frac{c \times p}{2}$,

$$= \tfrac{1}{4}\sqrt{(b+c+a)(b+c-a)(a+b-c)(a-b+c)},$$

$$= \sqrt{s(s-a)(s-b)(s-c)}.$$

2. Show that the area of an equilateral triangle, each side of which is denoted by a, is equal to $\frac{a^2\sqrt{3}}{4}$.

3. How many acres are contained in a triangle whose sides are respectively 60, 70, and 80 chains?

4. How many feet are contained in a triangle each side of which is 75 feet?

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BY

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